Open University Geological Society Journal
Spring Edition 2005

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Cover illustration: Thin sections of several different habits of barite. Photographs: Jane Clarke.

Botryoidal barite Mag 538; ppl.	Acicular barite Mag 549; xpl.	Poikilotopic barite Mag 530; xpl.
Bladed barite (white) Mag 580; ppl.	Botryoidal barite Mag 538; xpl	Spherulitic barite Mag 584; xpl.
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Two floating islands on a sub-Antarctic lake

Zoë N C Gardner

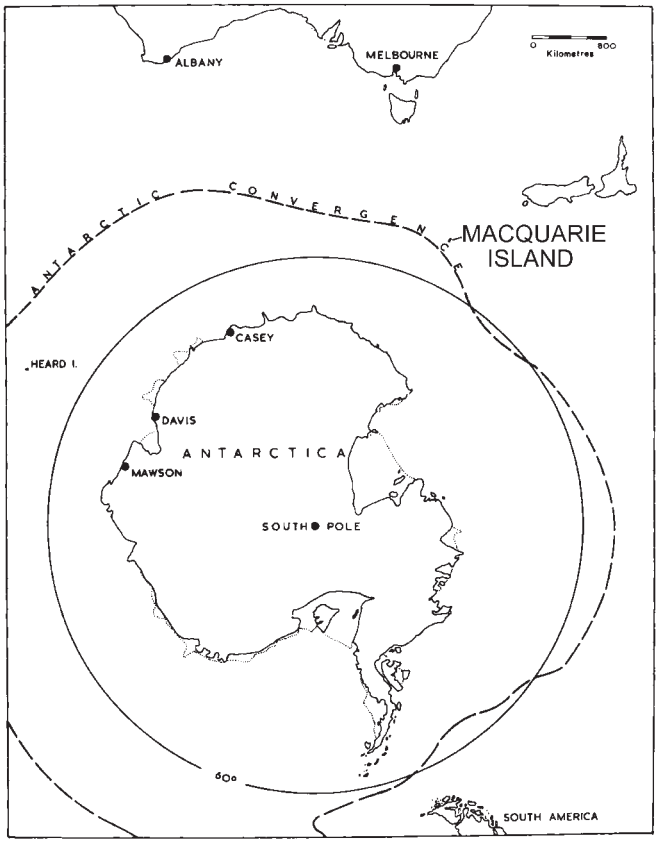

Figure 1. Location of Macquarie Island.

Introduction

Macquarie Island (54º30'S, 158º57'E) lies 1580 km southsouth-east of Tasmania, 1130km southwest of New Zealand and 1530km north of Antarctica (Figure 1). It is 34km long and 2.5-5 km wide with an area of 120km^2; its axis lies N15ºE. Topographically it is a plateau, 250-330m above sea level, with numerous mountains and valleys, bounded by steep slopes and cliffs descending to a raised beach terrace or directly onto the beach or in a few places into the sea. Geologically it is a mid-oceanic ridge horst, entirely composed of basic igneous rocks, predominantly pillow lava and volcanic breccia, except for interstitial *Globigerina* ooze and a small mud-stone outcrop on the west coast. The valleys contain glacial till, and other evidence of glaciation in the form of U-shaped valleys with undersized streams, roches moutonnées, glacial striae, erratic boulders etc. is abundant.

At present the Antarctic convergence lies approximately 240km S of Macquarie Island. The magnetic variation was 29ºE in 1976, having increased from 18ºE in 1911.

The climate is cold, wet and windy. The data in the Table in the Appendix were measured at the Australian National Antarctic Research Expedition's (A.N.A.R.E.) meteorological station on the isthmus which is 6m above sea level (a.s.l). They are mostly extracted from Jenkin (1972) with additions from E Jones (unpublished 1974), Taylor (1955) and Law & Burstall (1956). Of the several factors influencing plant growth, Jenkin considers shortwave radiation the most important (Jenkin 1972). On 80% of

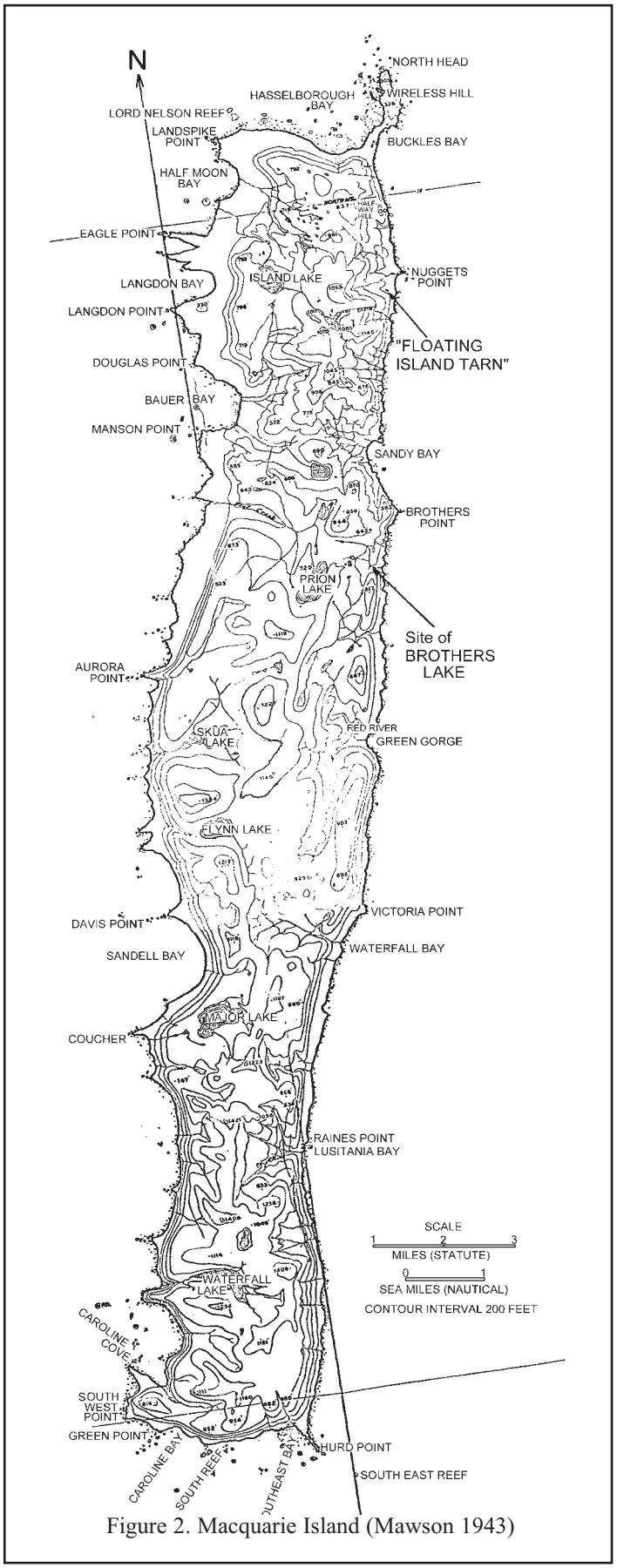

Figure 2. Macquarie Island (Mawson 1943)

Figure 3. The northern half of Macquarie Island.

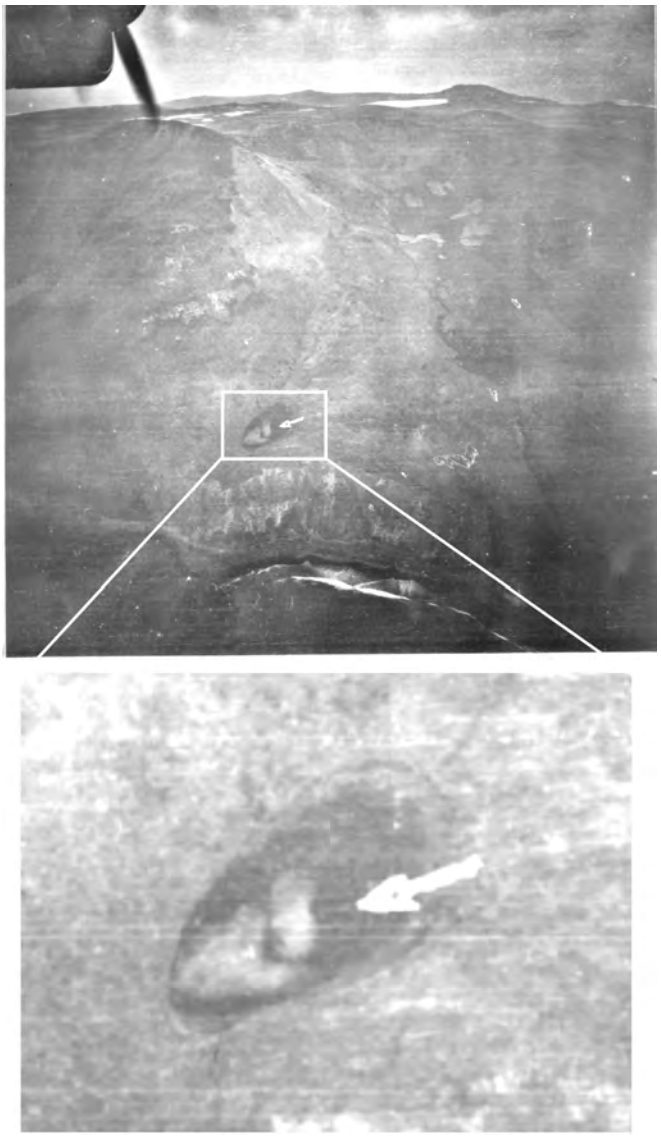

Figure 4. Oblique view of Floating Island Tarn. Mt Elder in the background. 1947.

the days of precipitation, this is <5mm; occasionally amounts up to 254mm have been recorded in one day. The figures in the Table are not representative of the island as a whole; the amount varies greatly with site due to the interaction of wind, topography and vegetation cover, with more on the east than the west side due to orographic effect.

Macquarie Island was visited by two botanists last century: J H Scott (in Taylor 1955), who found eighteen species of vascular plant in 1882, and A Hamilton (in Taylor 1955) who found thirty two species in 1894. It was occupied by an Australian Antarctic Expedition (A.A.E.) party from 1911 to 1914. L R Blake, the geographer/geologist, produced a topographical map (Figure 2) which is still more accurate than the 1971 map (Figure 3) , apart from a few changes in topography which have occurred since then (Mawson 1943). H Hamilton (1926), the biologist, found four more species of vascular plant, but did not find two which had been found previously (Cheeseman 1919; Hamilton 1926). The vegetation was mapped and its various formations described in detail in 1950-51 by B W Taylor, who also found two more species (Taylor 1955). A total of thirty-five angiosperms, of which three are introduced and three endemic, four pteridophytes, eighty bryophytes and fifty-five lichens have now been described.

A small lake separated from the large Nuggets valley by a ridge, is shown on Blake's map (Figure 2). It can just be seen on two of the 1947 aerial photographs, one of which is Figure 4, although the quality of the prints at this part of the island is very poor. Two islands, one elongate and one L-shaped can just be made out; indeed it is only by the recognizable shape of the islands that the lake can be identified at all – it looks like a drip mark on the film. That the islands float is shown by a comparison with the 1976 aerial photographs, one of which is Figure 5, where the L-shaped island has turned nearly 180º. This fact was discovered by W Vestjens, biologist, in 1962, when he was looking down from Mt. Elder and noticed the islands moving (Vestjens, pers. comm.). Sketches he made of the various positions in which he saw the islands were requested but not received; unfortunately he made no measurements. The existence of the islands apparently ceased to be common knowledge in 1967, but interest was revived in 1975 when a member of the 1967 party, P Ormay, returned to Macquarie Island.

I was a member of A.N.A.R.E. on Macquarie Island from February to November, 1976.

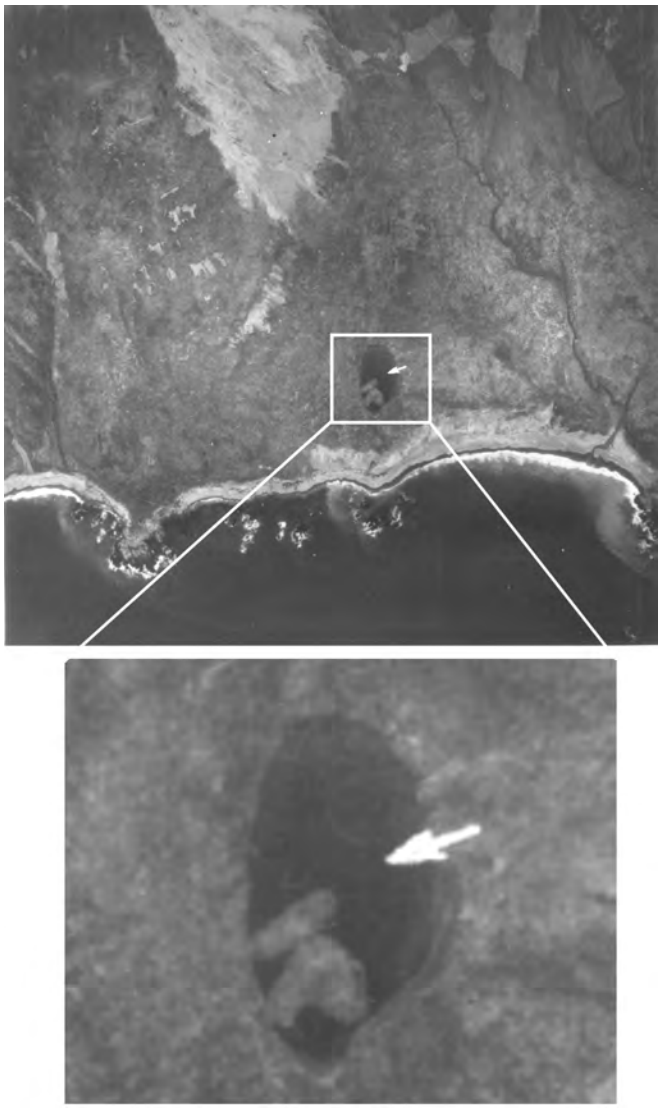

Figure 5. Detail of the two floating islands in the FI Tarn. 1976.

Objectives

The Aims of the Study were:

1) To describe the topography and vegetation of the floating islands, the tarn in which they are and the surrounding area with a view to providing an accurate base for comparison in future years. This will permit continuing documentation of changes in area, depth and vegetation and indicate what conservation measures may be needed to preserve what may well prove to be a unique botanical/geographical feature. Certainly it is unique to Australia.

2) To formulate a theory as to how these islands came to be formed.

3) In connection with 2, I decided to study a second lake, further south and higher up, in which five stationary islands exist, for comparison. It soon became apparent that these islands were of entirely different origin, that they were relicts of a quaking bog which once filled the valley, and posed a no less interesting problem. Therefore I conducted a parallel study of this system.

Description of study areas

1) "Floating Island Tarn" (Figures 5 & 6).

Figure 6. Floating islands on Floating Island Tarn from the lower slopes of Mount Elder. (© G W Johnstone)

Note: this name, suggested by G W Johnstone, is unofficial, as A.N.A.R.E. members are not permitted to name topographical features. However some name has to be used and it will hereafter be referred to as FI Tarn or the tarn.

The local topography is shown on Blake's larger scale map of the northern end of the island with 50' contours. This does not actually show the tarn, but correlating it with Figure 2, the tarn is clearly at the bottom of the steep basin with Mt. Elder southwest, the Nuggets Valley to the northwest and the coast to the east. In fact, the ground slopes steeply from Mt. Elder (371m) right to the bottom of the tarn. The other sides of the tarn are formed by a ridge from the lower slopes of Mt. Elder passing west and north of the tarn and meeting another east of it, the slope being again steep on the north but more gentle east and west. Over the ridge to the northwest lies the huge Nuggets colony of Royal Penguins (*Eudyptes chrysolophus schlegelii*). In summer there are several nests of the Southern Skua (*Stercorarius skua lonnbergi*) on the ridge, the birds feeding on carrion, eggs and chicks in the penguin colony. Over the ridge to the east is a steep cliff. On the geological map of Macquarie Island, the tarn overlies the junction between dyke swarms northeast and gabbro southwest. The basin appears to be of glacial origin; its cross-section is shown in Figures 7a & b.

The tarn, which is 41m a.s.l., is 122m long, 70m wide, up to 6m deep and is of a fairly regular oval shape. Most inflow is subterranean; I have never observed flow in the stream bed to the west, except for the last few metres; it presumably flows only after exceptionally heavy rain. All outflow is subterranean, the water percolating through the volcanic breccia and emerging 23m below

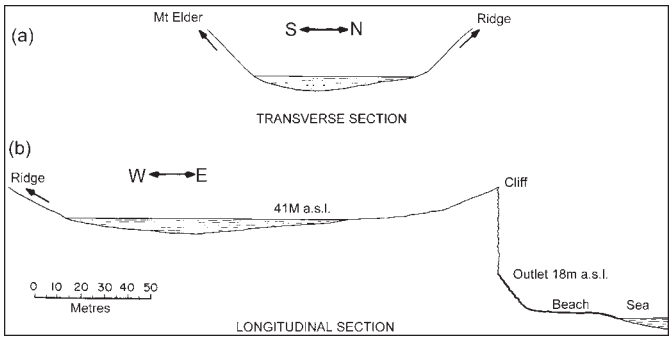

Figure 7. a) Transverse section of Floating Island Tarn; b) Longitudinal section.

Figure 8. Outlet stream from Floating Island Tarn emerging from the cliff. (© T C Hegerty)

the surface of the tarn through several holes in the cliff, none above 18m a.s.l. Hence the several small streams join and flow down a steep unstable scree slope to the beach of coarse sand, over which the water flows to the sea (Figures 7b & 8). Many lakes on Macquarie Island have similar underground drainage (Figure 2). There has always been a fair quantity of water flowing down this stream when I have observed it, but it is impossible to attempt to measure the flow, not only because of the irregular bed but because much of the water undoubtedly flows through, not over, the scree and sand.

The tarn is not shown on the 1971 map (Figure 3), which incorrectly shows a stream running through the location of the tarn.

2) "Brothers Lake" (Figures 9 & 10).
Note: this name, adopted because the lake lies immediately beside the Brothers' track about 2km south of Brothers' point, is also unofficial for the same reasons. The name "Brothers" is that of a sealing schooner. It will hereafter be referred to as Brothers Lake or the lake.

Figure 9. Oblique aerial view of Brothers Lake in 1947. Lake Prion is in the background.

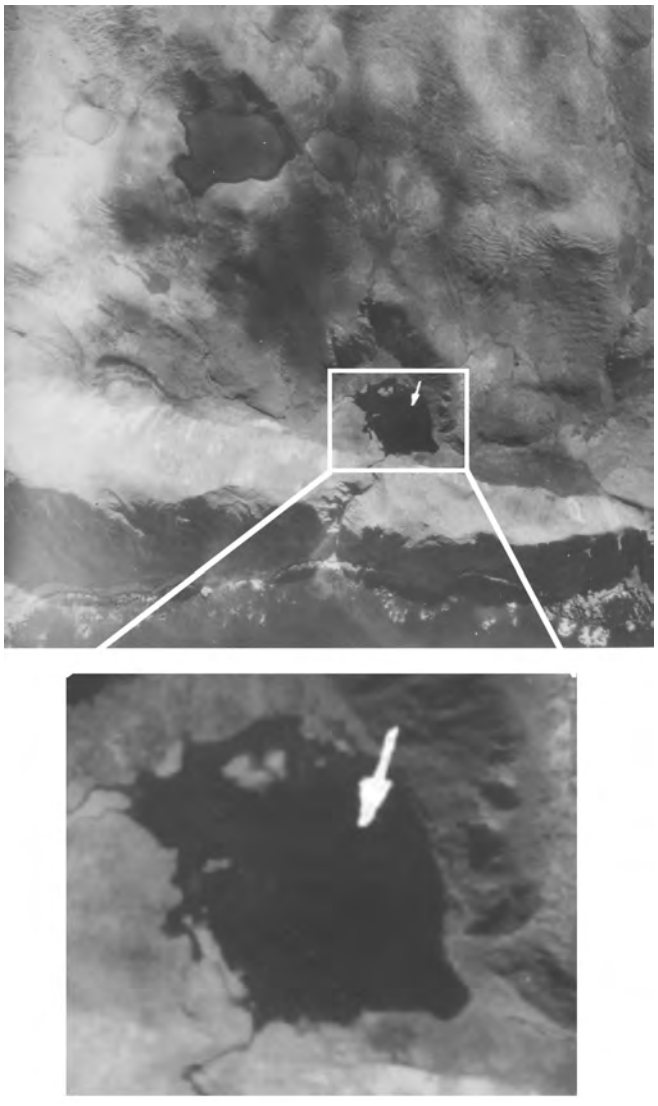

Figure 10. Vertical aerial view of Brothers Lake in 1976.

The location of the lake and its local topography are shown on Figure 3. Its general shape is square with a very irregular margin and a fairly uniform depth of 1.1m. It is almost completely surrounded by quaking bog. The bog zone is fairly narrow west and northwest, where it separates the lake from the steep ridge shown on Figure 3, 9, 10, & 12, and east where it separates the lake from a very low ridge through which passes the outlet stream (Figures 9 & 10). This then cascades down the scarp to the beach. To the northeast and especially south the bog is extensive and the main inlet stream meanders through it to enter the lake at its southwest corner (Figure 10). This stream is fairly wide and deep, with a clean sandy bottom and good flow at all times. On the geological

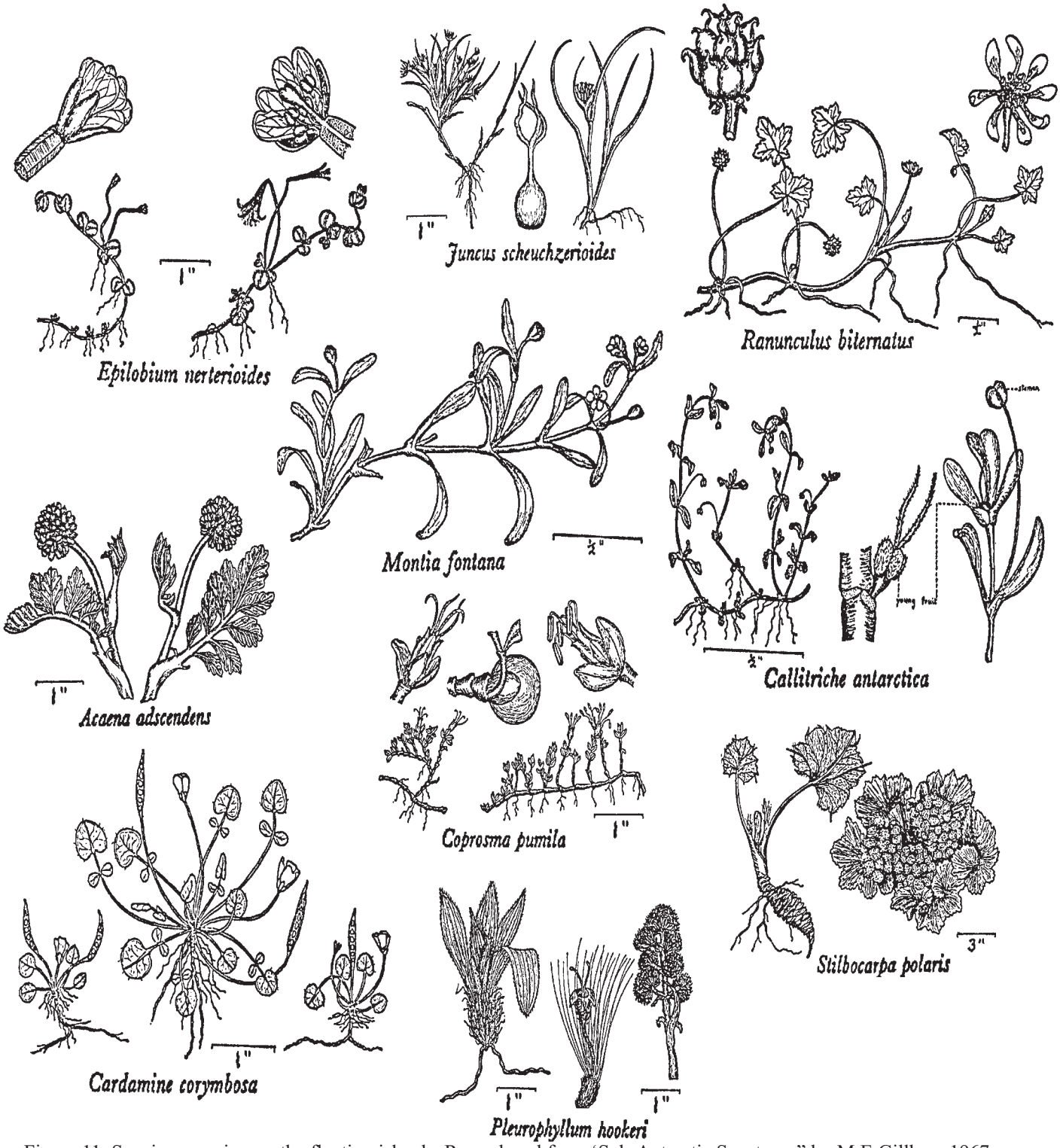

Figure 11. Species occuring on the floating islands. Reproduced from 'Sub-Antarctic Sanctuary" by M E Gillham 1967.

map of Macquarie Island, the lake lies well within the pillow lava/volcanic breccia zone. It is not shown on Blake's map.

Methods and results

Species : **A species list of plants was compiled.**

The Latin names are as used by Jenkin (1972). Hereafter all species will be referred to by the generic name only, *f.* or *a.* being added to *Poa* and *n.* or *l.* to *Epilobium*. The mosses *Breutelia* spp. and *Thuidium furfurosum* and the leafy liverworts *Lophocolea* spp. are collectively referred to as "moss" because they generally occur together and mixed. Line drawings of 10 of the species are reproduced in Figure 11 from Gillham (1967).

Survey

FI Tarn and all seven islands were measured; magnetic bearings of the axis of FI Tarn were taken and converted to true bearings (Figures 13 & 14). The altitude of FI Tarn and its outlet were measured with an aneroid barometer which was set at sea level.

Depth of water

Depth soundings of FI Tarn and Brothers Lake were taken with a large nut attached to a tape. Initially this was attempted lying on a lilo, but hypothermia and inability to counteract the wind by hand paddling resulted in failure. An inflatable 4ft x 3ft rubberised canvas boat, rendered porous by age and only designed

Figure 12. Taking depth soundings on Brothers Lake. (© T C Hegerty)

for mouth inflation, with two single paddles, was therefore used. A valve was inserted in the inflation hole so that the boat could be inflated to tenseness by bicycle pump. The obvious holes were patched so that deflation was slowed. A broomstick shaft and plywood blade were added to one single paddle to convert it into a collapsible double paddle, so that the boat could be controlled in any wind. (Figures 12, 14 & 15).

While the positions of the depths recorded from the shore and from the edges of the islands are accurate, those in open water are only approximate. As soundings were shouted out from the boat, my assistant ashore noted the estimated position on a sketch map.

Description

The topography and vegetation of the tarn and lake and their shores, surroundings and islands were examined. Sketch maps were drawn. The terminology used to describe the vegetation is that of Taylor (1955).

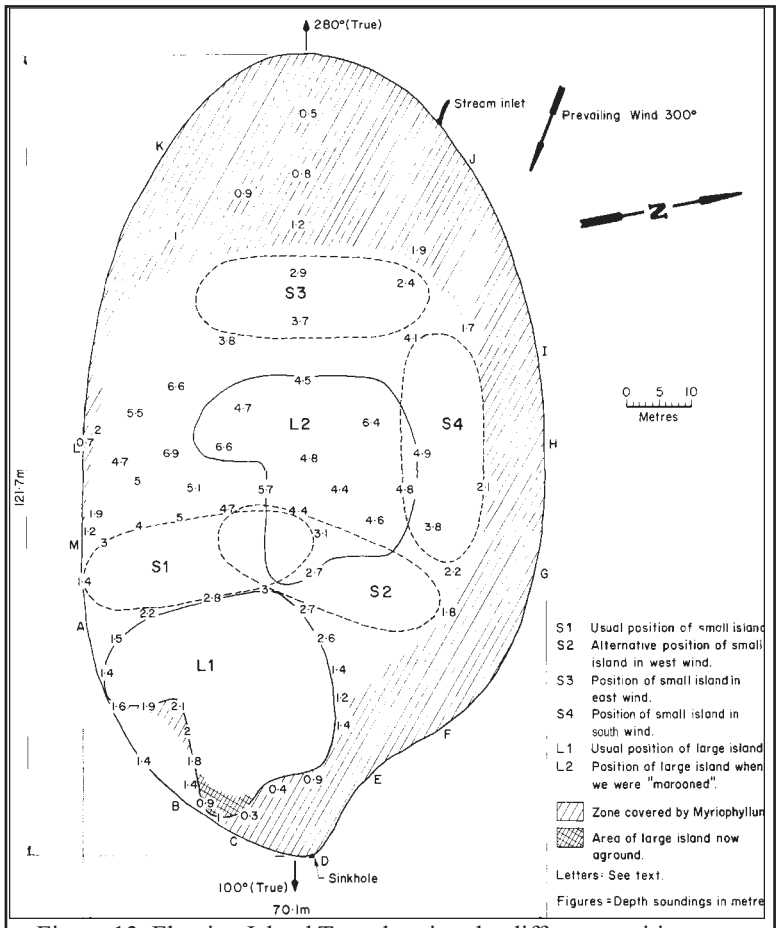

Figure 13. Floating Island Tarn showing the different positions of the floating islands.

"Floating Island Tarn" (Figures 6 & 13)

Surrounds: The steeper hillsides surrounding the tarn are covered with wet tussock grassland, while the gentler slopes are a form of sub-glacial herbfield (Figures 6, 16, 17, 18 & 19).

Shore: Letters refer to Figure 13. Also see Figures 16, 17 & 18.

A - B: The wet tussock grassland (*Poa f. - Stilbocarpa - Polystichum* association) continues right to the tarn edge, which is slightly undercut and about 30cm above the normal water level (Figure 21a). The side of the tarn is vertical and layered peat is visible for about 0.5m.

B - C: Transition to

C - D: Sloping edge with *Poa a.*, moss, *Juncus, Ranunculus* and *Callitriche* encroaching over the water. The water is only 15-30cm deep 0.5m out from the edge.

D: There is a sinkhole about 30cm in diameter and 30cm below the level of the water. Water trickles over the *Myriophyllum* strands into it most of the time, but westerly gusts pile water up against the eastern edge of the tarn and cause it to flow into the hole and fill it a few cm deep; this rapidly drains away.

D - E: Transition to

E - F: Edge as A - B but water shallow (Figure 21b). Abrupt change at F to

F - G: Sloping edge without encroachment, 15-30cm deep.

G - H: Depth similar; edge *Acaena* and *Poa a*. with *Poa a.*, moss, *Juncus, Ranunculus* and *Callitriche* encroaching over the water.

H - I: Transition zone with sloping edge, about 30cm depth of water and a little encroaching vegetation.

I - J: Edge irregular (Figure 21f). Outjutting sections covered with overhanging *Poa f.*, 30-60cm above water level. Indentations filled with moss, *Poa a*. dominants, with *Ranunculus, Juncus* and *Cardamine*; some encroachment. Average depth 30cm.

J - K: Gentle slope of *Poa a*. and moss, the latter most abundant near the stream inlet. *Callitriche* and *Juncus* encroaching. Water very muddy with an average depth of 15cm.

K - L: Similar but only narrow (average 1m) band below *Poa f. – Stilbocarpa – Polystichum* association. Encroaching vegetation mainly *Juncus* and moss. 0.30–1m deep outside zone of encroachment.

L – M: Transition to

M – A: *Poa f. – Stilbocarpa – Polystichum* association extends to edge at water level (Figure 21c). Side of tarn vertical.

Surface: *Myriophyllum* occupies the zone too shallow ever to be entered by the islands (Figures 4, 5, 13 & 16). It also occurs in the bays in the large island and all small indentations in the irregular edges of both islands. There are some filamentous algae, probably mainly *Rhizoclonium* sp., *Spirogyra* sp. and blue-green algae, growing on the *Myriophyllum* opposite the H - I and K - L segments of the shore.

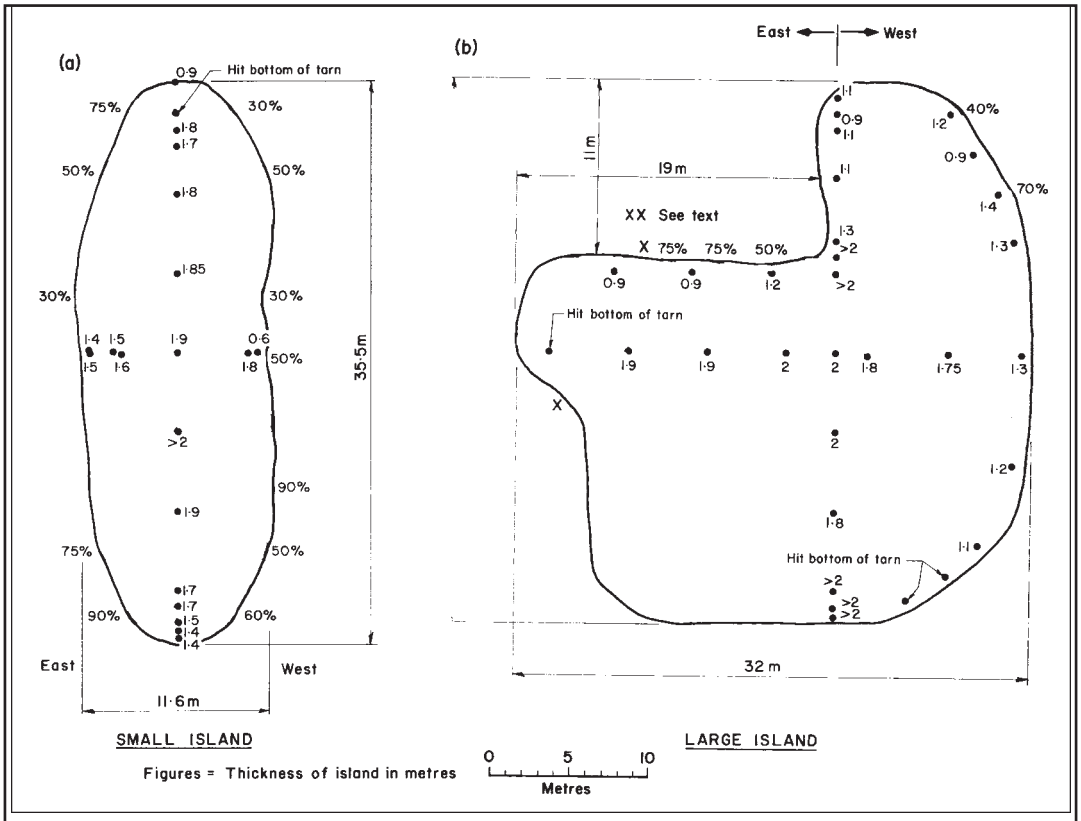

Figure 14. Thickness of the two floating islands in Floating Island Tarn.

Floating Islands: (Figure 14). Figure 16 shows both islands from the southeast with the small island (Island S) in position S2 (Figure 13). Figures 17 and 18 show the same section of shore (M - B) taken from the large island (Island L) which is in the foreground in positions L1 and L2 respectively. Figures 19 and 20 show S in position S3 taken from the south and north ends respectively of L which is in the foreground in position L2. The section of shore I - J is in the background of Figure 18 and J - K in that of Figure 20.

S is overall much wetter than L; the central area of L is variable but in general drier than the edge. After standing for a minute anywhere the feet were always in water up to 15cm deep and in places near the edges it was not possible to stand that long without water overflowing the calf-length boots. *Poa f.* occurs mainly around the edges, but is not continuous; there is a dense patch at the east end of L and isolated plants occur throughout. *Stilbocarpa, Pleurophyllum, Coprosma, Festuca* and *Marchantia* occur only in the drier areas, although local depressions surround individual *Stilbocarpa* and *Pleurophyllum* plants; there is no *Stilbocarpa* on S. *Callitriche* and *Poa a*. only occur near low edges, in the absence of *Poa f.* or outside this. *Callitriche* and *Ranunculus* extend over the water.

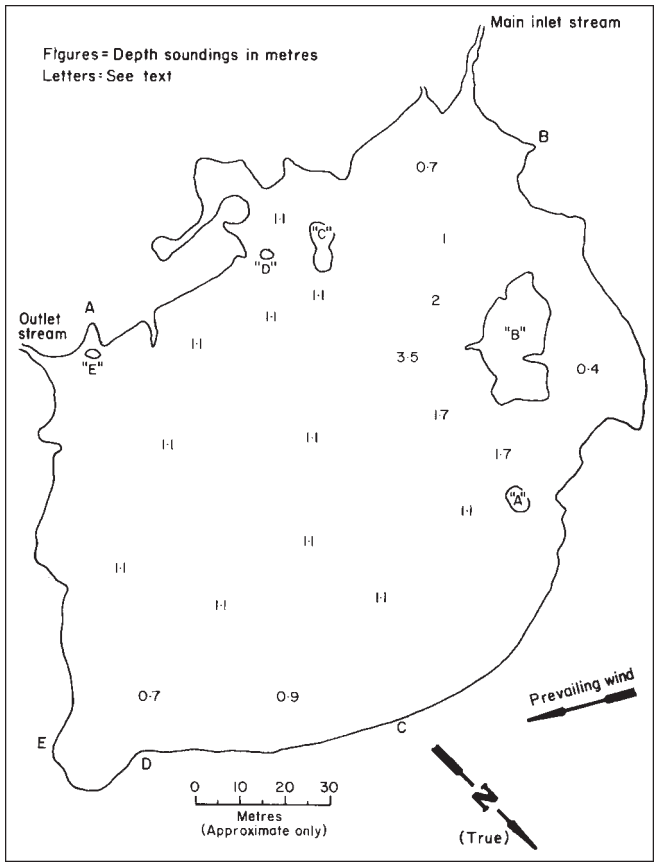

Figure 15. Depth of Brothers Lake.

"Brothers Lake" (Figures 9, 10 & 15).

Shore and Surrounds: Quaking bog surrounds the lake except for gravel between C and D which is immediately below a hill covered with *Agrostis* and *Acaena* as dominants. Between A and B and D and E are alluvial fans overgrown with quaking bog. The quaking bog is advancing over the water from all sides and has a very irregular margin, dropping down into 0.5 - 1m of water with a thick very soft mud bottom. The quaking bog is composed mainly of mosses and liverworts with vascular plants of mat habit: *Ranunculus, Montia, Callitriche, Epilobium, Cardamine*;

Figure 16. The floating islands from the southeast. (© T C Hegerty)

Figure 17. The south shore of Floating Island Tarn taken from the large island while it was against the shore. (© G W Johnstone)

Figure 18. The same section of shore as in Figure 17 taken from the large island while it was in the centre of the tarn. (© G W Johnstone)

Figure 19. The small island taken from the south end of the large island while both were in the centre of the tarn. (© G W Johnstone)

and *Juncus* and *Poa a*. around the edges. It is possible to walk over much of it by keeping to patches of *Marchantia*. The lake for many metres out is full of dead *Myriophyllum* covered with filamentous algae. No live *Myriophyllum* was seen on the surface but a piece was brought up on a paddle blade. There are, mainly on the west and south sides, several "semi-detached" islands of quaking bog, many of the larger ones being walkable if they can be

Figure 20. The small island taken from the north end of the large island while both were in the centre of the tarn. (© G W Johnstone)

reached. They are separated from each other and the main mass by leads containing varying proportions of open water, algae supported on dead *Myriophyllum*, mosses, *Ranunculus, Callitriche, Juncus* and *Poa a.* Most such leads are uncrossable but some can be crossed on hands and knees and a few on foot. Several "semi-detached" islands are visible in Figure 10. They appear to be attached securely to the lake bottom and one another and/or the main mass by the interlacing dead *Myriophyllum* stems incorporated in the growing vegetation. An attempt to detach the smallest (0.5m diameter) by prodding with a track marker post, resulted only in submerging it.

Relict Islands: (Figure 10).

"B" (Figure 15). Mainly *Agrostis* with patches of *Pleurophyllum* near north end, *Poa f.* at south edge and mosses in south half. East edge raised and supporting *Acaena*; west edge of mosses, *Juncus, Ranunculus, Callitriche* and filamentous algae encroaching over the water. None of the sides of the island is sloping; parts are vertical (Figure 21h) or undercut (Figure 21i) or with a shelf 30–60cm below water level and with remains of *Agrostis* and *Acaena* visible on this (Figure 21j). Very wet; waders essential for walking over island as the water would have been over boots in much of central part of island; it is higher at the south end and most of the north section. The channel (visible in Figure 10) contains *Juncus, Ranunculus, Poa a.* and mosses and is not walkable: neither is the area north of the west part of transect C. There is evidence of flooding in the form of stranded filamentous algae along both edges.

"A": (Figure 15). Mainly *Agrostis* with the west edge mosses, *Juncus* and *Ranunculus* encroaching over the water. Very wet except the east edge; both edges similar to the corresponding edges of B.

"C": (Figure 15 and 23). Almost all *Poa f.*, except the south end which is mainly *Agrostis* and *Acaena.* Higher end drier than any other island studied, relict or floating. Edge similar to east edge of B; no encroaching vegetation.

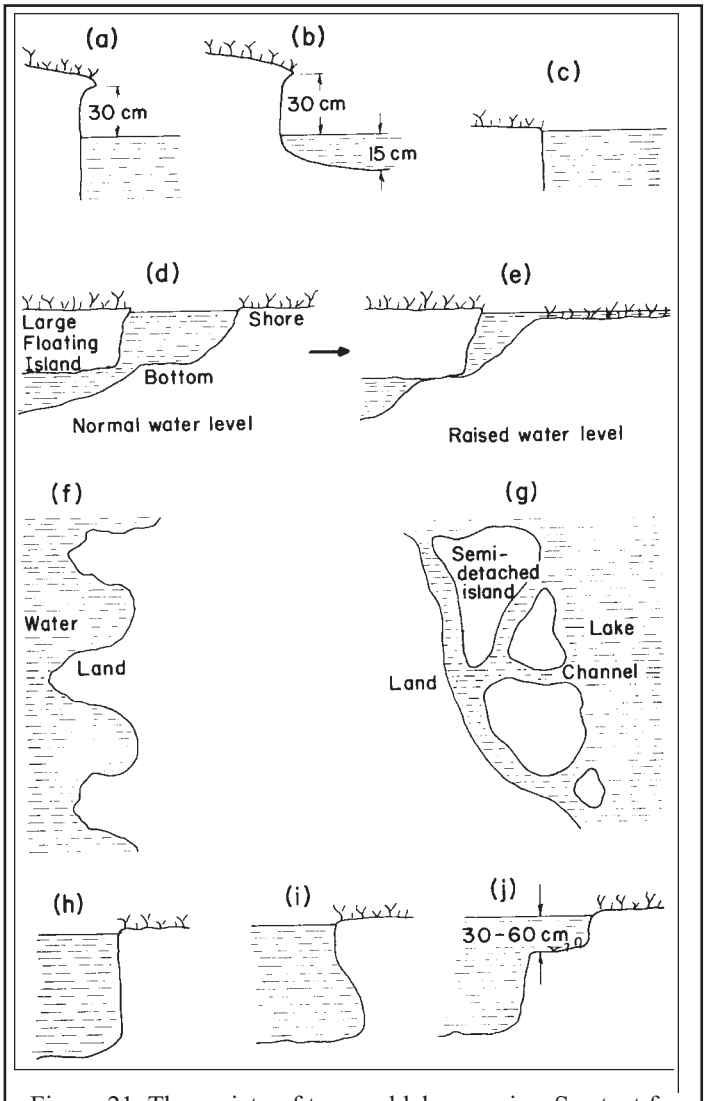

Figure 21. The variety of tarn and lake margins. See text for discussion.

"D": (Figure 15 and Figure 10). Resembles A; very wet; of similar composition throughout. Edged by shelf covered by dead vegetation 30cm below water level.

"E": (Figure 15 and Figure 10). Resembles A and D. Abrupt raised west edge, mainly *Acaena,* sloping to east edge with vegetation, mainly *Callitriche*, encroaching over water.

Thickness of floating islands

A "depth gauge", consisting of two wooden strips bolted eccentrically to a wooden spear and graduated in 10cm divisions up to 2m, was made (Figure 24). With this, the thickness of the two floating islands was measured in various places (Figure 14). It was inserted with the spear pointing down vertically; this was then levered into the horizontal position and the gauge was withdrawn as far as possible and the scale read at ground level.

The depth gauge was also used in the insertion position to measure the depth of the tarn along its edges and the lake around the relict islands and to check that the relict islands were entirely composed of peat. It was used in the use position to ascertain the undercutting of the sides of these islands.

The thickness of both floating islands is 1.50-2.00m except in some places near the edge, with L on the whole thicker than S.

Figure 22. Sink hole at the edge of Floating Island Tarn. (© T C Hegerty)

Fauna

Mammals and birds present on the islands and birds on the tarn and lake were noted at each visit, as was evidence of their past presence.

Samples of plankton were taken and were sent for specialist examination.

Vertebrates: Species observed on the floating islands at one or more visits:

Rabbit (*Oryctolagus cuniculus*): introduced.

Southern Skua (*Stercorarius skua lonnbergi*).

Dominican Gull (*Larus dominicanus*).

Giant Petrel (*Macronectes halli* and/or *giganteus*).

Black Duck (*Anas superciliosa*).

There was evidence of much use by the above and also by feral cats (*Felis catus* - introduced) in the form of rabbit and cat scats; rabbit-chewed *Pleurophyllum* and *Stilbocarpa* leaves; scratched-up moss, collections of regurgitated gizzard stones and balls of feathers. No penguin egg shells or marine mollusc shells were seen. The excreta of all species must contribute significantly to the enrichment of the soil water.

The flat areas around the edge of the tarn also show much evidence of use by all the above fauna. No penguins appear to enter the valley containing the tarn, presumably because there is no easy access from the sea: a steep climb up scree or a *Poa f.* - *Stilbocarpa* clad slope is required.

Figure 23. Island “C”, Brothers Lake. (© G W Johnstone)

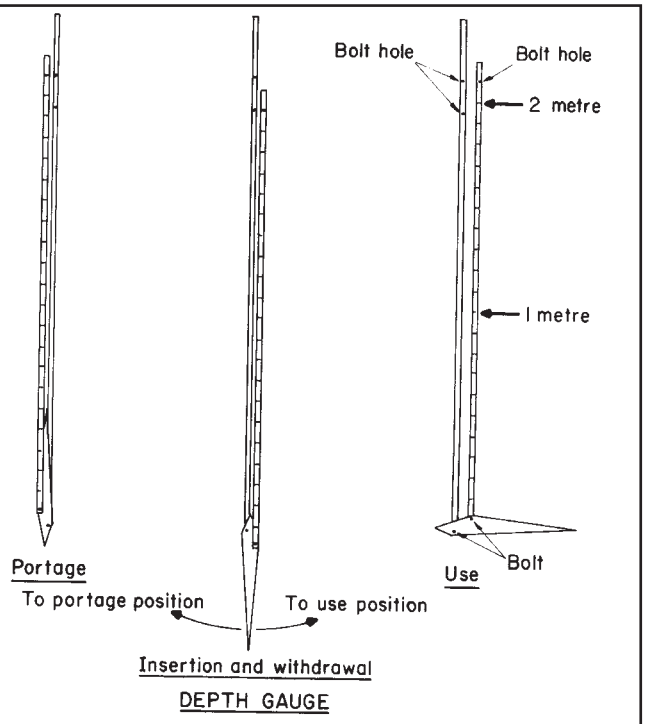

Figure 24. Home-made depth gauge.

The shores of Brothers Lake show similar evidence of fauna to those of the tarn. On the relict islands there are no scats or chewed leaves and the moss is undisturbed. Marine mollusc shells, rabbit remains and feather balls were seen on island B indicating use by skuas. Island D was covered with limpet shells, probably brought by Dominican Gulls.

Invertebrates: The water of FI Tarn is teeming with Copepods. *Pseudoboeckella brevicaudata* is the common species on Macquarie Island. As it possesses twelve different life stages no attempt was made to identify these or to search for other species. One other copepod, five cladocerans including *Daphnia carinata*, and one ostracod are known to occur on Macquarie Island (Evans 1970).

Conductivity of water

Samples of water were taken from FI Tarn and their conductivity measured as an index of the ionic concentration of the water. This would indicate whether fen or bog vegetation, as per Taylor's (1955) classification, might be expected.

The conductivity of the main body of water in the tarn was 296mho/cm and that of the water trapped between the large island and the bank was 310mho/cm, both corrected to 25ºC. Although low, these are about average for freshwater on Macquarie Island (Evans 1970). Poor fen peat would thus be expected.

Photography

Copies of photographs taken by several people were requested. See figures. The majority, taken by N Brothers, were not received.

Sampling of vegetation

A collapsible plywood metre quadrat was made. Tapes were laid out on each island and quadrats sampled on a regular grid system on the floating islands (Figure 14) and at regular intervals along transects on the three larger relict islands. One central quadrat was sampled on each of the two smaller relict islands. A few quadrats were also sampled on the "semi-detached" islands around Brothers Lake and in the leads between them. None were done on the shore of FI Tarn as there was no vegetation there similar to that on the floating islands. Difficulty was experienced in keeping the tapes in position as tent pegs were powerless to hold them, the ground being so soft, against the efforts of the wind and skuas to carry them off.

No macro fungi were present on the floating islands on the dates of sampling (4.11.76 for S and the eastern section of L and 5.11.76 for the western section of L) but they had been noticed on previous visits. No plant species were present on the floating islands which were not recorded in the quadrats. Unfortunately the work was necessarily done early in the season, before most species were in flower or had even reached their full vegetative development. I failed to distinguish between the leaves of *Agrostis* and *Juncus* or between those of *Montia* and *Callitriche*. This was pointed out by J Jenkin when he visited the island at the end of my stay there, and he confirmed my identification of the other vascular species and identified the bryophytes. Also the percentage cover of certain species, in particular *Cerastium*, but probably also *Ranunculus, Epilobium l.* and *n*. and *Acaena*, was less than it would have been later in the season. On the relict islands, *Cardamine* was present on A and moss on D and these were not recorded in the quadrats.

Percentage cover of each species present was estimated in each quadrat sampled. From this the total number of 10 x 10cm squares occupied by each species in the total area of each island sampled was estimated and thence the mean percentage cover of each species.

Various statistical tests were done on the data. These showed a much greater difference in species composition between the two floating islands, between edge and centre quadrats on the floating islands (but not the relict islands) and between the floating and relict islands than is apparent on casual observation.

Classification of vegetation

Taylor (1955) does not define fen and bog according to pH; his fen peats have pHs ranging from 3.4-4.8. He defines rich fen peats as occurring where the ground water is high in dissolved salts due to a high percentage of drainage water; poor fen peats as occurring where the ground water is low in dissolved salts due to a low percentage of drainage water; bog peats as occurring where the ground water is very low in dissolved salts due to absence of drainage water. Of fen, he says that the *Juncus* association is typical of rich fen peat in upland valley bottoms. Of bog, he says that this occurs on wet flats at all levels where water is received only as rain and not by lateral drainage. Of herb field, he says that the *Pleurophyllum*: *Cerastium* sub-association occurs on low-level river flats, the *Pleurophyllum*: *Stilbocarpa* sub-association on flats at all levels, the *Coprosma* sub-association on slopes. Of the ecotone between grassland and herbfield, he says that this occurs in low level valleys with small flat areas. Of the aquatic communities, he says that these occur in ponds.

Thus any of these except the *Coprosma* sub-association might occur in the bottom of the valleys. On his vegetation map Taylor marks the site of FI Tarn as a small patch of herbfield in the midst of grassland. In fact, the composition of the vegetation of the islands does not correspond with that of any of the alliances, associations or communities, but shows some features of most. It is probably a seral not a climax community.

The vegetation of each island is not homogeneous; there appear to be two main reasons for this. Although the water table appears to be at ground level throughout each island (except for a few small sections of edge), there are actually small differences of 1-5cm which are reflected in the local occurrence of different species over small areas. The edges of the islands receive a larger percentage of drainage water than their centres. Because of their movement, more drainage water is likely to percolate through to the centre of the floating than the relict islands; also it can penetrate in from below as well as from the sides; but the floating islands are larger than the relict islands. Because of its small size and the fact that much of its drainage is from the surrounding ridges and from Mt. Elder, the water of FI Tarn probably contains a higher percentage of drainage water and this probably has a higher concentration of mineral salts, than that of Brothers Lake (whose conductivity was not measured) which receives most of its drainage water through peat and which, because of its larger size, receives a higher percentage of rain water. Also the water in FI Tarn both enters and leaves by multiple routes and is kept well mixed by the movements of the islands, while that of Brothers Lake has one main entrance and exit and, away from the current between these, is mixed only by wind. These differences are reflected in the differences between the centre and edge of each island and between the islands of the tarn and lake.

Wind exposure does not vary greatly as all islands are in valleys down which the wind blows fiercely, but relict islands A & B are theoretically relatively protected from the prevailing westerly wind. This was not noticeable while working on them in typical Macquarie Island weather and I do not consider this likely to be a significant factor in vegetation differences.

The depth of peat is only significant where it is too thin to support *Poa f.* at the growing margins of islands.

Other islands

Islands on other lakes on Macquarie Island were observed from the lake shores.

There is an island on Skua Lake (Figure 2), which is a plateau lake. It is a "conventional" island of gravel with sloping sides, covered by vegetation.

There are several islands in the lakes of the Red River system (Figure 3). All appear to consist mainly or entirely of *Poa f.*, are not far from the shore and are separated from it only by shallow water (<15cm) or in drier weather by mud only. They cannot be reached on foot as the surrounding quaking bog is unwalkable.

Research

All available past literature on Macquarie Island was searched for references to FI Tarn or Brothers Lake; none was found. The date of discovery of the floating islands was traced by telephoning various ex-A.N.A.R.E. biologists and medical officers around Melbourne, Canberra and New South Wales.

Discussion

The Formation of the Floating Islands

Theoretically these could have formed by colonization of masses of floating detached vegetation by mosses and other mat-forming plants, and thus have been afloat from their inception. Although masses of detached *Myriophyllum* and algae do occur on Square Lake (Figure 3), it is likely that they get broken up by storms and changes of wind direction and no colonizing plants have ever become established. If such colonization occurred, small islands would be much more likely to be found than the two massive ones which exist. Also, islands so formed would be very thin with shelving bases whereas both islands are 1.5-2.0m thick with sides approaching vertical.

It seems likely that the islands were formed attached to the shore and later detached. Although there is no evidence of this type of process around the shore of FI Tarn, a possible mechanism for its occurrence can be seen in Brothers Lake. Here "semi-detached" islands of from 0.5m to many metres in diameter occur. The way these form appears to be as follows:

Myriophyllum grows up from the bottom in water <2m deep. Each stem becomes colonized by filamentous algae which eventually kill it, but it remains anchored to the bottom of the tarn. The algae from adjacent stems become intertwined forming a mat on the water surface. This is colonized initially by mosses, *Ranunculus* and *Callitriche*. When these have become established and formed a firm mat other species follow. So the quaking bog gradually extends over the lake. The living vegetation remains at or just above water level; so, as peat forms, the thickness of the quaking bog gradually increases until the peat rests on the mud at the bottom of the lake. Where minor streams reach the edge of the quaking bog, formation of the algal mat is retarded and a lead remains, which may be split into two or more divisions. Thus the "semi-detached" islands, separated by leads, are formed. So long as they are in contact with open water, they continue to grow, but leads separating them from the main mass of quaking bog may close over. A gale, from the direction of the main mass, and/or a storm-raised water level may put a considerable strain on the dead *Myriophyllum* stems, no doubt weakened by decay, holding a large island to the bottom and adjacent islands or the main mass. These may break or become uprooted setting the island free to float over to the lee shore. Where this is gradually sloping, the island would be likely to be blown aground and remain there, unless freed by a gale from the opposite direction, and be gradually incorporated in the main mass on that side of the lake. But if the shore is steep, the island could remain afloat indefinitely.

With the configuration of Brothers Lake, it seems possible that the fate of some of the "semi-detached" islands now in existence on the south and west sides may be to have a short free life and then to become incorporated in the east side of the lake. However the level of Brothers Lake is unlikely to become significantly raised as it has a free outlet not liable to obstruction (but see second section of discussion), so the "semi-detached" islands may never break free.

The situation in FI Tarn is somewhat different. Here the south side of the tarn is steep and the east and north sides probably were formerly. Vegetation is encroaching over the water on parts of the margin (Figure 25), although at present there is no sign of "semi-detached" island formation. The outlet for the water is through many metres of rock and this may be inadequate after heavy rainfall. Also the lower passages through the rock may become silted up, resulting in gradual permanent raising of the water level of the tarn. That this has happened in Major Lake is evidenced by the existence of a surface outflow channel in 1950 (plate 25 from Taylor (1955)) while none existed in 1911-14 (Figure 2 and Mawson 1943). (On the other hand, new passages may open up through the rock; Blake (in Mawson 1943) found evidence of an old outlet channel from the north end of Prion Lake (Figures 3 & 9) to Flat Creek 5m above the then surface of the lake (Mawson 1943)).

Figure 25. West end of Floating Island Tarn showing colonisation of plants over the surface of the water. (© T C Hegerty)

If "semi-detached" islands formed on FI Tarn, conditions would be suitable for them to become detached and not to run aground. However this has now happened to L. On-my first visit, L followed S out into the centre of the tarn with a very light east wind. On my second visit, there was much detached *Myriophyllum* stranded over an extensive area of the east shore. On this and subsequent visits L did not move although S floated to various positions as shown in Figure 13. While "marooned" for an hour on my first visit, there was nowhere where we could stand still for more than 2-3 minutes without water coming over our boots. On later visits, it was possible to stand on the section of edge marked XX on Figure 14 indefinitely without water reaching the boots. On one occasion a rabbit was disturbed in a "squat" in this area; rabbits do not lie up where the water table is at ground level. So this section of edge is now evidently raised above water level. It appears that a westerly gale and heavy rain raised the water level of the tarn, depositing *Myriophyllum* over the east shore, and caused L to override a shelf on the side of the tarn (Figure 21d & e). As the water level subsided, the island became stranded. An easterly gale with heavy rain – much less common – will be needed to shift it again. The presence of the patch of *Poa f.* on this corner of L suggests that this sequence of events may have occurred before.

The floating islands may have been in existence for a long time, even centuries, although Blake does not note their existence in 1911-1914. They undoubtedly existed in 1947 (Figure 4) and yet were not noted by Taylor in 1950, although he visited the area as evidenced by the fact that he shows a small patch of herbfield in the surrounding grassland at exactly the site of the tarn. Efforts to trace him have been unsuccessful. Twenty-three other biologists were on Macquarie Island between 1948 and 1962, when the floating islands were discovered. Several, and other expeditioners, must have been on Mt. Elder or the scarp surrounding the Nuggets valley and therefore have been in a position to observe FI Tarn. Two, one of whom spent three years on Macquarie Island, have confirmed that they did (A M Gwynn and S Csordas - pers. comm.). It is not visible from the beach or from the overland track (Figure 3), so would not be seen by those walking up or down the island. Since the existence of the floating islands ceased to be generally known in 1965, a further seventy two biologists have been on Macquarie Island, including one botanist who has been annually for 10 years (J Jenkin pers. comm.). Probably none of those who saw the tarn had ever seen a floating island before, and they did not recognize the significance of the clustering of the two islands in the lee corner of the tarn. I did, having seen floating islands on Lakes Victoria and Kyoga in East Africa, although I would probably not have noticed them had I not been looking for them. The biologist who took me to look for the tarn did not believe they were afloat when he saw them, even though he had been told they were by another biologist. He only became convinced when an easterly wind blew the island on which we were standing into the middle of the tarn, "marooning" us until a westerly wind blew it back to shore. It seems probable that Blake, who also would have been unlikely to have seen a floating island before, could have seen them and, not seeing them move, not realised their nature.

Unfortunately the basis of the above argument is unsound. *Myriophyllum* was not found in 1880, 1894 or 1911-14 when plant collections were made. Taylor, in 1950, only found it above 100m; the tarn is 41m a.s.l. Now it is common, even on the coastal terrace.

A further suggestion, put forward by J Jenkin, is that the peat layers of a quaking bog which once existed at the east end of the tarn were split horizontally as the water level rose as described previously. However, it is difficult to see how, in this case, lateral detachment occurred.

The Formation of Brothers Lake

Neither this lake nor the southern inlet stream which now forms its main source (Figure 10) are shown on Blake's map (Figure 2), only streams from the north and west which are at present very insignificant. Since his mapping was undoubtedly very meticulous and accurate and he shows many much smaller lakes (including FI Tarn), it may be assumed that it did not exist in 1911-14. It must have come into existence some time between 1914 and 1947, when it can be seen in the aerial photograph (Figure 9). It is not shown on Taylor's map, but he has used a copy of Blake's map on which three small lakes including FI Tarn are not reproduced. He did not alter the topographical detail of the map where this had changed as exemplified by the fact that he shows no outlet stream from Major Lake although he mentions this in his text (Taylor 1955).

Before the formation of the lake, it appears likely that the entire valley was covered with quaking bog, of which the five islands are remnants, continuing to erode over part of their circumference but growing on other parts. How the rest of the peat became washed away to a depth of over 1m might have been connected with one or more of three events which might have occurred during the intervening time.

It seems probable that a very minor stream in the valley south of the lake may have cut back and captured the water of the next lake to the south along the Brothers' track (see Figure 10) to form the main stream which now enters the southwest corner of Brothers Lake (formerly draining into Red River system (Figure 2).

Macquarie Island was uninhabited from 1919 to 1948. At some period in this interval the Antarctic convergence may have been

much further north than at present. Mawson states that when he visited Macquarie Island in 1931 small icebergs were sometimes seen from the land and several icebergs were stranded at the south end (Mawson 1943). None has been seen in recent years.

The outlet stream might have become blocked in one of two ways. It passes through a low ridge connecting two hills. It is too far from either hill for a landslide to dam it, but a cave-in of one bank might have done so. It not infrequently happens on Macquarie Island that a stream crossing peat cuts down forming a deep channel across which vegetation grows, eventually forming peat above the stream which becomes subterranean. Later the roof may cave in blocking the stream, which then recommences to flow over the surface. All stages of this process can be seen on Macquarie Island, but usually in high-moor not fen or bog peat .

After returning to the U.K. several years later, I discussed my findings with two botanists with a particular interest in bogs. Dr. D Goode, formerly of the N.C.C., informed me of the existence of the phenomenon of "bog bursts" and supplied me with a long list of references to such occurrences in Europe, perusal of which gave rise to the formulation of the theory below, which now seems the most likely explanation for the situation in Brothers Lake.

A glacial trough was formed and deepened by the convergence of glaciers from north and south. After the ice melted, a glacial lake remained, impounded by the ridge, through which the outlet stream gradually cut down to its present level. Both ends commenced to infill with silt brought down by the two main inlet streams. Over this silt, bog vegetation grew in from the edges of the lake (as is happening at present) until the entire area was covered apart from the streams and one small pond (shown on Figure 2 and located by the deeper soundings on Figure 15). A section of the area at this time would have shown layering as in Figure 26: The degree of decomposition increased with depth. As the decomposed peat sunk to the bottom, its fluidity increased. As the level of the bog rose with the accumulation of further vegetation, it became increasingly unstable, with the upper layer of vegetation overlying semi-liquid mud.

Prolonged exceptionally heavy rain on one occasion between 1917 and1947 caused the bog to swell and finally to burst. Mud and water drained away carrying the loosened vegetation. Once the underlying mud was no longer protected by vegetation, progressively more drained away, eventually carrying most of the vegetation with it. The lake was therefore re-established with a few islands of relict peat and vegetation from the bog remaining. Filling from the edges recommenced as soon as the latter stabilised. This cycle may well have been repeated more than once since the glaciers retreated.

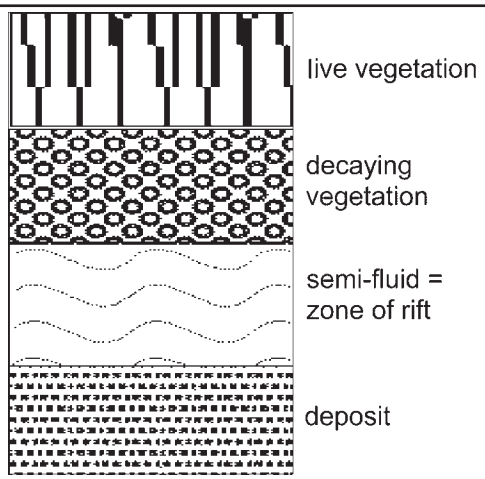

Figure 26.Suggested layering in the proto-Brother's Lake.

I wrote to the expeditioners to ask that the height of the ridge through which the outlet stream passes be measured, and also to enquire the maximum depth of peat known anywhere on the island and the supposed time of the last glaciation. Regretfully I did not receive an answer.

Comparable Processes in other Parts of the World

Floating papyrus islands occur in northern Africa and South America. Individual tussocks float freely in a lake on the North Island of New Zealand (A Davey pers. comm.).

Islands, floating on the surface of the water but not free to move around, occurred on the Lagoon of Islands in Tasmania (Tyler 1976). The lake, about 1km square, at 200m, was covered with a floating mat of reeds (*Chorisandra cymbaria* and *Baumea rubiginosa*) with interlacing rhizomes, underlying 10-50cm of water and overlying about 2m of peaty water. The mat was just walkable. The lake bottom consists of banded peat and mud overlying gravels on dolerite, the lowest peat being about 5000 years old by carbon-dating. Islands were formed by tussocks of sedge (*Carex appressa*) raising the soil above water level, followed by colonization by terrestrial angiosperms including tea-tree (*Leptospermum lanigerum*) and bottle-brush (*Callistemon viridiflorus*), and eventually by trees including *Eucalyptus* spp. up to 10m high, with 50-100 bushes on the larger islands. The weight of this growth then depressed the island and a "moat" was formed around it; waterlogging of the roots caused death of all species and eventual decay and break-up of the island leaving a pool in the mat with woody remains at its base. It is presumed that reeds grew over this to complete the cycle. The lake has now been dammed, flooding and killing off the reed mat and all species on the islands. I have visited it twice and it now consists of open water with patches of reeds (unwalkable). Dead trees and bushes are still visible but none is near the shore; I did not have a boat. A similar process occurs on the edges of the Shropshire meres in England. Free-floating islands are not, to my knowledge, formed.

Request

Any further suggestions as to how either the floating islands or Brothers Lake might have been formed would be most welcome. Information regarding or references to any floating islands existing on lakes in other temperate areas of the world would also be greatly appreciated.

Acknowledgements

This study would have been quite impossible without the assistance of many past and present members of A.N.A.R.E., during both the field work and the writing up.

My biggest debt of gratitude is to T C Hegerty, mechanic, Macquarie Island 1976, who spent several days carrying a heavy pack between base and study areas and taking notes, gloveless, in cold and frequently rain or snow, in a script which is still legible. He also made the depth gauge, modified the boat and paddle, lent his waders and took some of the photographs.

G W Johnstone, A.N.A.R.E. biologist, took me to look for the floating islands, took some of the photographs, encouraged me to undertake the study, offered many helpful suggestions and criticised the manuscript.

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Appendix

METEOROLOGICAL DATA FOR ANARE

Air Temperature:	Mean Annual	4.7ºC
Air Temperature:	Mean Diurnal Range	3.4ºC
Air Temperature:	Mean Monthly Maximum (January)	6.7ºC
Air Temperature:	Mean Monthly Minimum (July)	3.1ºC
Air Temperature:	Extreme Maximum recorded	12.4ºC
Air Temperature:	Extreme Minimum recorded	-8.9ºC
Soil Air Temperature: (-10 to -100 cm)	Mean Annual	5.5ºC
Day Length:	Maximum	17.3 hours
Day Length:	Minimum	7.3 hours
Sunshine:	Mean Annual	2.2 hours/day (18% of possible)
Sunshine:	Mean Monthly Maximum (Jan & Feb)	3.3 hours/day
Sunshine:	Mean Monthly Minimum (June)	0.8 hours/day
Shortwave Radiation:	Mean Annual (0.3 – 3.0 u)	70 Kcal/cm/year on a horizontal surface
Cloud Cover:	Mean Annual (predominantly low stratus)	83%
Relative Humidity:	Mean Annual	89.2%
Barometric Pressure:	Mean Annual	998.4 mb
Barometric Pressure:	Extreme Maximum recorded	1036.1 mb
Barometric Pressure:	Extreme Minimum recorded	948.5 mb
Precipitation:	Mean Annual Total	926 mm
Precipitation:	Mean Daily Total	2.5 mm
Precipitation:	Mean Annual Days of which includes	317 days
Snow:	Mean Annual Days	106 days
Precipitation:	Mean Monthly Days	24-28 days
Precipitation:	Evaporation Ratio	2.08
Wind:	Mean Direction	300º (WNW) (very little NE-ESE)
Wind:	Mean Speed 5 m above the ground	8.6 m/sec (19.2 mph)
Wind:	Maximum Gust recorded	46.9 m/sec (105 mph)

Welded ignimbrites on Gran Canaria: an introduction and field guide to selected locations

Duncan Woodcock

Introduction

Volcanism on the Canary Islands is predominantly basaltic. However, during the geological evolution of the islands of Tenerife and Gran Canaria, shallow magma chambers developed that allowed the production of felsic magmas by fractional crystallisation. On Tenerife, eruption of these magmas resulted in a varied suite of pyroclastic fall, surge and flow deposits that outcrop mainly in the south of the island. In contrast, on Gran Canaria eruptions of felsic magmas were almost entirely of pyroclastic flows, many of which show spectacular welding. These crop out in some magnificent scenery in the arid south of the island (Figure 1) and are the subject of this paper.

Figure 1. Sequence of lower Fataga Formation ignimbrites, Barranco de los Vincentes. The lower, welded zones of each ignimbrite are more resistant to erosion than the upper, unwelded zones – producing a characteristic stepped topography reminiscent of the "trap" topography developed in sequences of basaltic flows.

Geological History

Table 1 provides an outline of the geological history of Gran Canaria. In common with most of the Canary Islands, there appears to be an early "shield-building" phase, separated from a later "post-erosional" phase by a period of intense erosion with little volcanic activity. This paper concentrates specifically on the Felsic Group; details of the other groups can be found in recent publications such as Carracedo & Day (2002).

The Felsic Group resulted from a period when a shallow magma chamber developed under a large volcano in the centre of the island (Perez-Torrado & Carracedo 2002). The magma chamber was fed periodically by a deeper basaltic source and underwent fractional crystallisation to produce a range of felsic magmas. These magmas were erupted mainly as pyroclastic flows, producing deposits with a total thickness of around a thousand metres. The products of the initial phase of felsic volcanism, known as the Mogán Formation, have a total thickness of around 300m and comprise eighteen cooling units. These cooling units are predominantly ignimbrites with subordinate lava flows: the lower units comprise silica-undersaturated phonolite and trachyte compositions while the upper units become increasingly rhyolitic and peralkaline. The later phase of volcanism, represented by the Fataga Group, comprises around 700m of trachytic and phonolitic ignimbrites, with lava flows becoming increasingly abundant upwards.

Figure 2 provides an outline stratigraphy of the Mogán and Lower Fataga Formations (Crisp & Spera 1987, McDougall & Schmincke 1977). Individual cooling units, each of which may comprise multiple flows that were erupted in quick succession, are identified by a letter, such as P1: a thick and laterally extensive ignimbrite that marks the base of the Mogán Formation. There are differences in detail in the stratigraphies presented by different authors in the Lower Fataga Formation, principally because the lava flows and occasional conglomerate beds are restricted locally, in contrast to the ignimbrite units.

Figure 3 shows the extent of the Mogán and Fataga Formations (ITGE 1992). They cover much of the SW of the island, where they are magnificently exposed in coastal outcrops, road cuts and in the walls of the "barrancos": steep sided valleys that have been

Table 1. Outline geological history of Gran Canaria

Phase	Age		Geological activity
"Post-erosional"	3 Ma to present	Plio-Pleistocene to Recent volcanism	Mainly alkali basalt lavas and pyroclastics. Most recent eruption c.1500BC
	5.5 to 3 Ma	Roque Nublo Group	Development of central stratovolcano, multiple oversteepening and collapse events. Low temperature, lithic-rich ignimbrites
"Erosional"		Erosional hiatus	Period of intense erosion
"Shield-building"	14 to 9 Ma	Felsic Group	Large volume pyroclastic eruptions from shallow felsic magma chamber
	14.5 to 14 Ma	Basaltic Group	Main shield-building activity: submarine , emergent and subaerial.

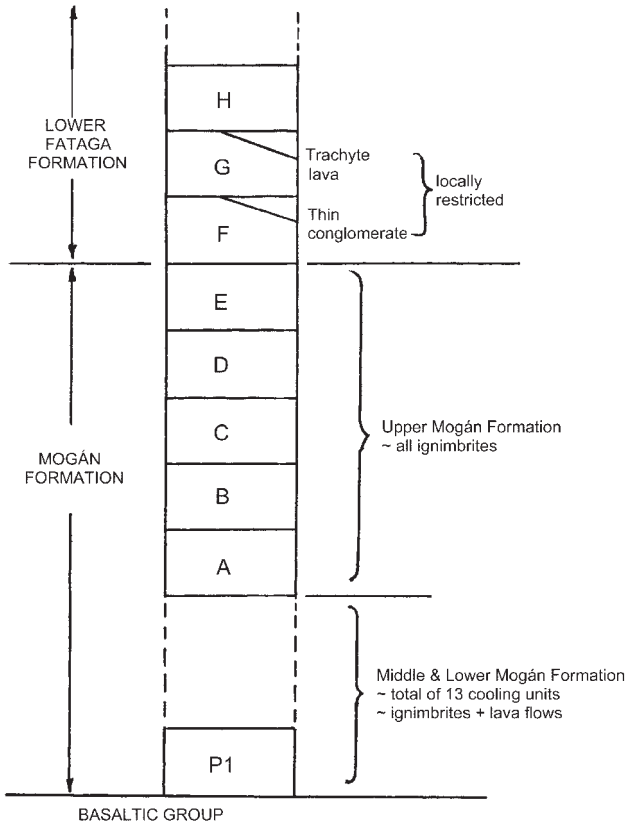

Figure 2: Outline stratigraphy of the Mogán and Lower Fataga Formations.

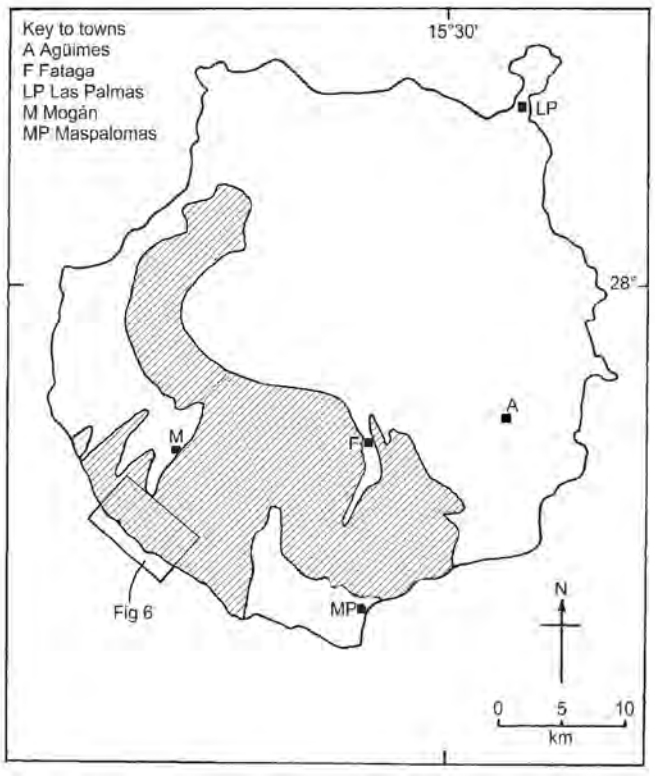

Figure 3: Map of Gran Canaria showing extent of outcrop of the Felsic Group (shaded).

incised by sporadic intense rainstorms. In addition, there are a number of isolated exposures in the SE of the island, in particular around Montaña de las Carboneras and around the town of Agüimes.

Welded Ignimbrites

Many of the ignimbrite units in the Mogán and Fataga Formations are welded; some are so intensely welded that they look superficially like lava flows. These "eutaxites" were first described by von Fritsch and Reiss in the 1860s, who described them as having "a fragmental structure but with an external lava-like appearance". They correctly interpreted their formation to be " the result of the refusion of tuffaceous materials" (Fuster *et al.* 1968). Controversy continued to surround the origin of these and other ignimbrites until it was finally settled in favour of a particulate origin.

An ignimbrite is thus a particular type of deposit from a pyroclastic flow produced by the fountain-like collapse of an eruption column or by a laterally inclined blast (Branney & Kokelaar 2002). Ignimbrites are typically rich in pumice fragments and volcanic glass shards produced by magma fragmentation within a volcanic conduit. They may be loose and unconsolidated, indurated by subsequent mineral deposition as the deposit cools or welded.

Figure 4. Eutaxitic texture in a block of Mogán D ignimbrite, Barranco de los Frailes. Note the subhorizontal foliation, defined by the flattening of pumice fragments into the characteristic elongate shapes called fiamme, and the way in which these fiamme are deformed round the numerous lithic clasts. Field of view *c*. 300mm by 400mm.

Welding occurs when the deposit is sufficiently hot for the vitric pumice and shard components to deform under stress. The resulting foliation is known as a eutaxitic texture, manifest at outcrop by the flattening of pumice fragments into the characteristic ragged, elongate shapes called fiamme (Figure 4). Ignimbrites vary in their degree of welding, from barely detectable to intense, depending on the chemical composition and volatile content of the deposit, together with its temperature and the degree of stress experienced. The intensity of welding can also vary through the vertical height of a cooling unit, with units typically showing an unwelded upper zone where the pyroclastic material has been subjected to lower temperatures and lower stresses.

Some intensely welded ignimbrites display an extreme elongation of fiamme that is difficult to explain by a simple flattening due to

the weight of overlying material. In addition, they show evidence of hot ductile deformation such as flow folding. This "rheomorphism" is usually considered to be the result of ongoing movement, or the remobilisation of a flow deposited on a sloping surface.

Ignimbrites continue to stimulate controversy, despite the basic question of their origin being settled. There are currently two models for ignimbrite deposition (Branney & Kokelaar 1992). One model envisages the emplacement of a pyroclastic flow as a plug of material whose motion "freezes" *en masse*; the other model considers the deposit to be built up gradually by deposition from the basal unit of a flow. Additional controversies surround the timing of welding relative to deposition and the relative importance of temperature and volatiles in the welding process. Detailed studies of the ignimbrites of Gran Canaria continue to add to the debate.

I took the opportunity to examine some of these ignimbrites during a recent visit to Gran Canaria in January 2004. My accommodation was in the town of Agüimes in the SE of the island. On arrival, I was surprised (and delighted!) to find that the local church and plaza was constructed almost entirely from blocks of welded ignimbrite. Apparently these blocks had been quarried from a small outcrop a couple of kilometres south of the church in the late eighteenth century. The blocks provide a good opportunity to examine two adjacent sections at right angles: Figure 5 shows photos of two adjacent surfaces, one parallel to the foliation and one at right angles to the foliation, showing a moderate degree of welding (Figures 5a & b).

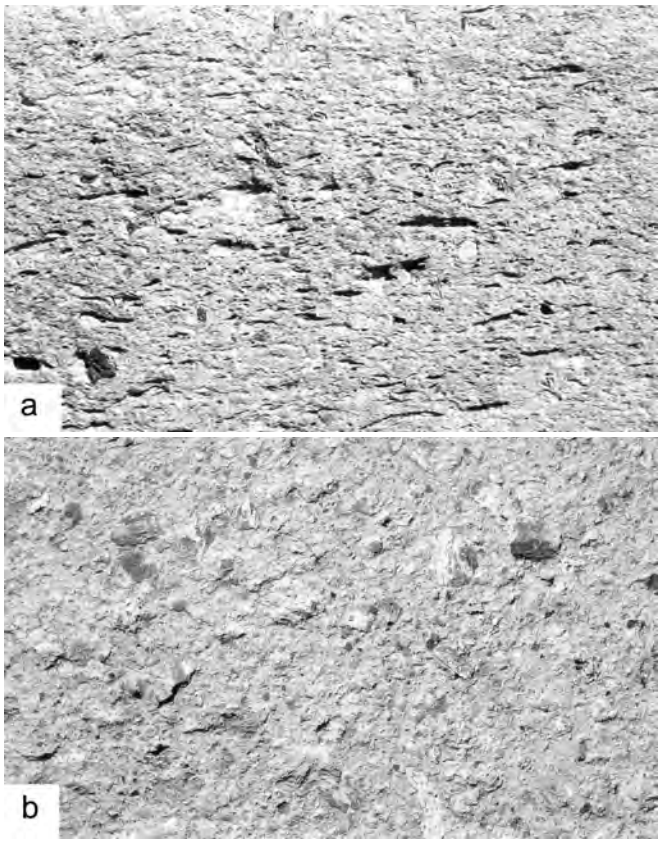

Figure 5. Two views of adjacent surfaces of a block of moderately welded Fataga ignimbrite, west wall of Agüimes church. Field of view *c*. 150mm by 230mm. (a) face of block at right angles to the foliation, showing a moderate degree of welding. (b) face of block parallel to the foliation with an apparently unwelded texture.

Geological Locations

Figure 6 comprises a sketch map of part of the SW coastal area of Gran Canaria, where the Upper Mogán and Lower Fataga ignimbrites are particularly well exposed. Three areas are particularly easy to access and were examined in detail: the areas around Barranco de los Frailes and Barranco de Tiritaña and the exposures along the road from Puerto de Mogán to Veneguera.

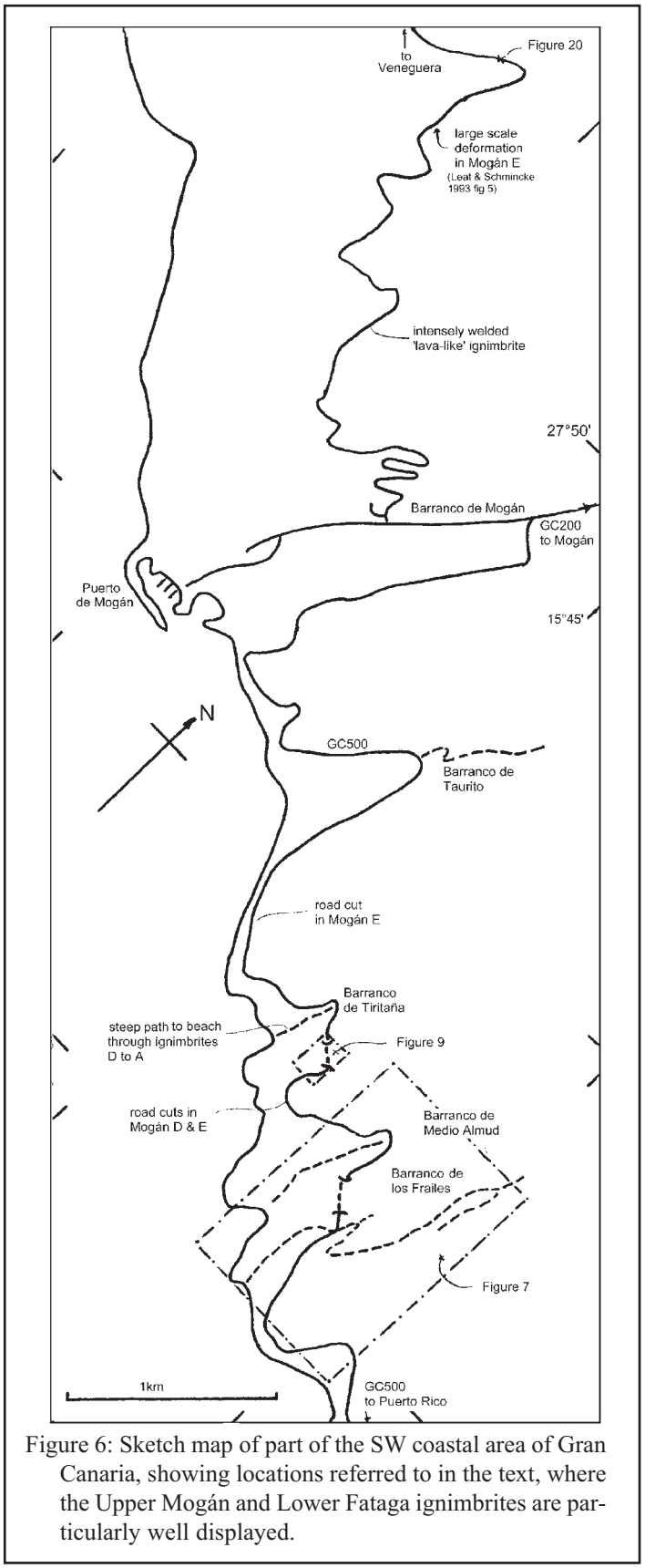

Figure 6: Sketch map of part of the SW coastal area of Gran Canaria, showing locations referred to in the text, where the Upper Mogán and Lower Fataga ignimbrites are particularly well displayed.

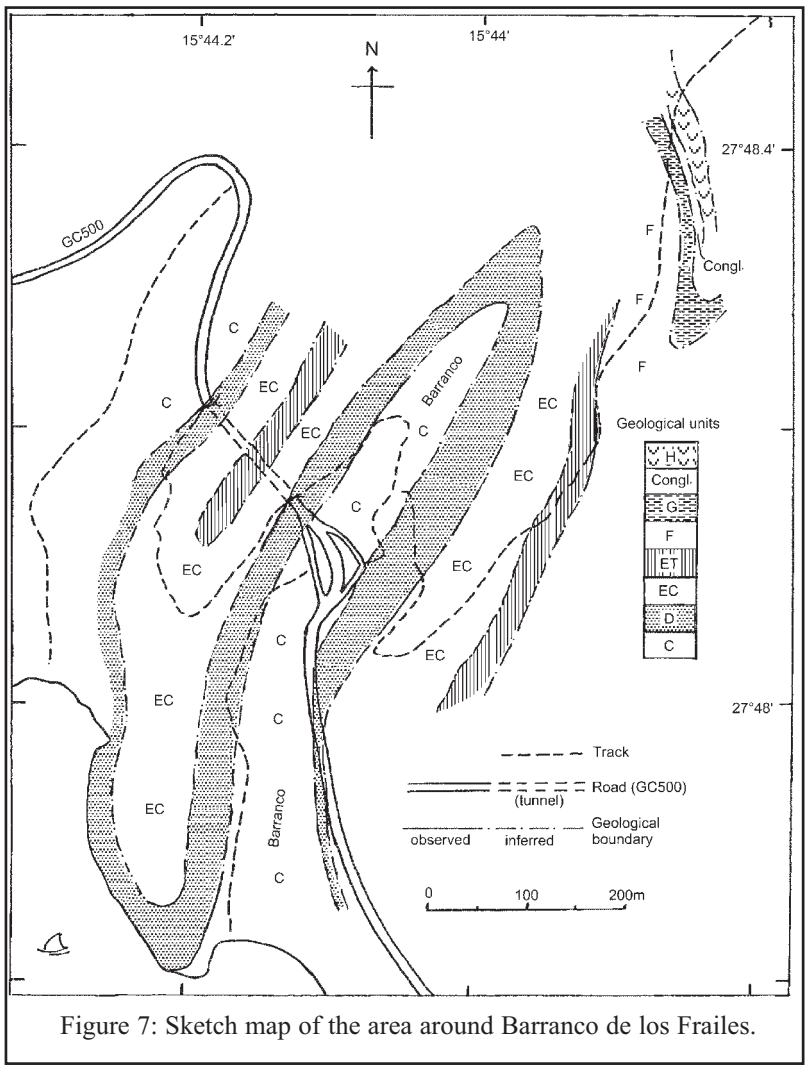

Figure 7: Sketch map of the area around Barranco de los Frailes.

Barranco de los Frailes area

A sketch map of this area, based on my own observations, is presented in Figure 7. Three traverses are particularly instructive:

i) Along the bed of the barranco upstream (NNE) from the parking area over exposures of the Mogán C ignimbrite and into the Mogán D unit.

ii) A track that starts from the barranco floor, crosses over the GC500 road at the SE end of the road tunnel and then loops SW and then north to the NW end of the road tunnel. This traverse contains some excellent exposures in the Mogán D and E units.

iii) A dirt road from the parking area to the bend at 27° 48.04' N 15° 44.06' W that then trends NNE, ascending the east wall of the barranco through a sequence of five ignimbrites that are well exposed in road cuts.

Figure 8 shows a composite section, based on observations from this area and the Barranco de Tiritaña traverses below. Note that the Mogán E cooling unit is a composite unit comprising a lower "EC" unit and an upper "ET" unit. The nature and significance of these subdivisions is discussed later in the paper.

Barranco de Tiritaña area

Two useful traverses in this area include:

i) A steep path down the barranco from the road bridge to the sea: this passes through the Mogán D and C units into excellent exposures of the underlying lithic-rich Mogán B and A ignimbrites.

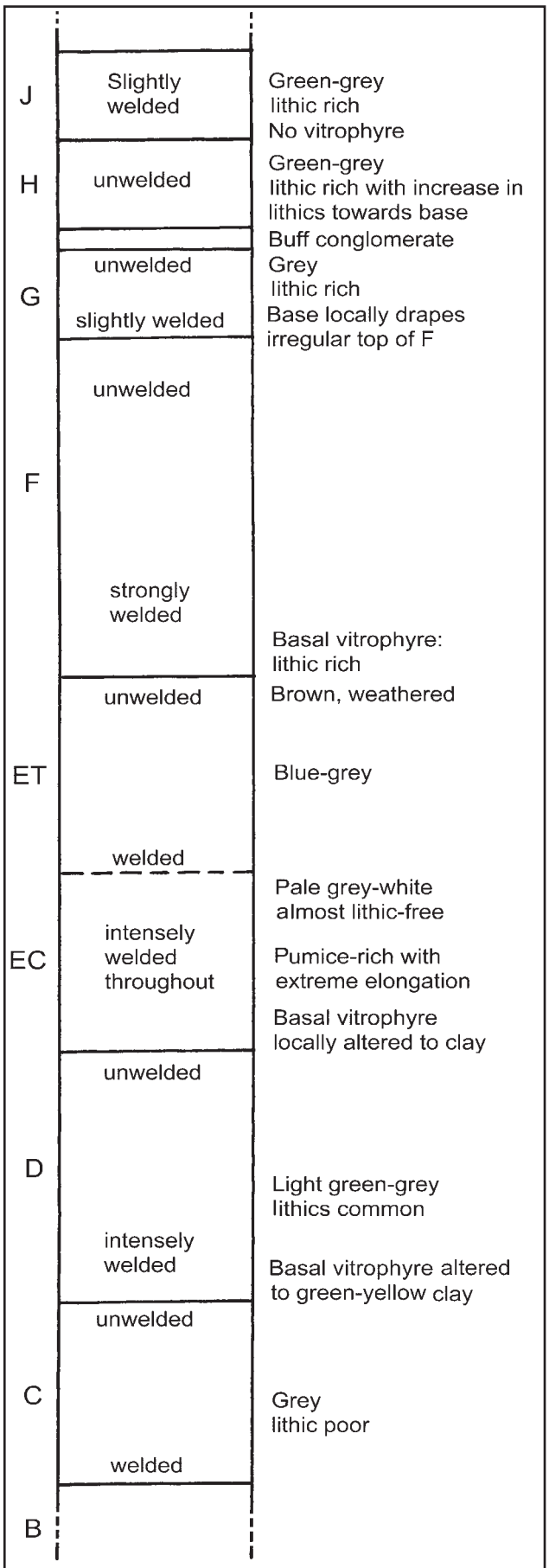

Figure 8: Composite section through upper Fataga and lower Mogán Formations, based on observations from traverses in Barranco de los Frailes and Barranco de Tiritaña (Figure 9).

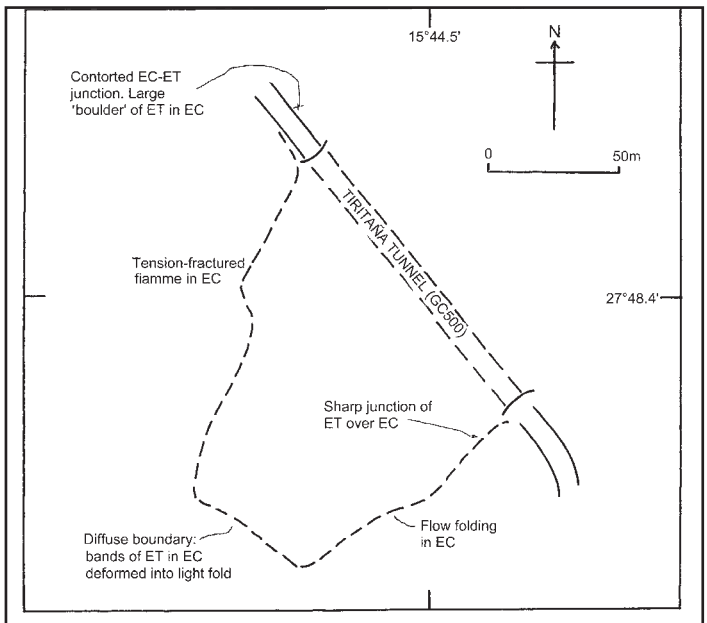

Figure 9: Sketch map of a traverse along the track round the Tiritaña GC500 road tunnel. EC and ET refer to the lower, comenditic and upper, trachytic divisions of the composite Mogán E ignimbrite.

ii) A track which loops round the Tiritaña GC500 road tunnel: this has magnificent exposures of the composite Mogán E ignimbrite. An annotated sketch map of this traverse is presented in Figure 9.

Puerto de Mogán – Veneguera road

The first five kilometres of this road contain a number of exposures of Mogán E ignimbrite showing deformation structures on a range of different scales.

Description of Mogán Formation Units D and E

Units D and E of the Mogán Formation are particularly well exposed in the locations mentioned above. Furthermore they are both peralkaline and rhyolitic in composition and in places show evidence of rheomorphic flow. The remainder of this paper describes some of the features of these two units in detail.

Mogán Formation, Unit D

Unit D is a multiple flow, single cooling unit with a total thickness of 10-15m. It is pantelleritic in composition and comprises four zones (Kobberger & Schmincke 1999) that differ in fabric as a result of different responses during deposition and subsequent rheomorphic flow:

i) A basal zone around 0.1-0.2m thick, now represented by a yellow-green clay band, but locally preserving patches of the original unaltered black glassy chilled margin of the flow (Figure 10).

ii) The overlying zone, around 2-3m thick, that is strongly welded with a number of shear sense indicators, such as rotated lithic clasts with asymmetric pressure shadows (Figure 11). The asymmetry invariably indicates top to downhill movement, suggesting that this zone sustained rheomorphic flow in response to deposition on a sloping surface.

iii) A zone which is strongly welded with a fabric that shows principally symmetric features (Figure 12) suggesting that this zone responded principally by flattening in response to the overlying load.

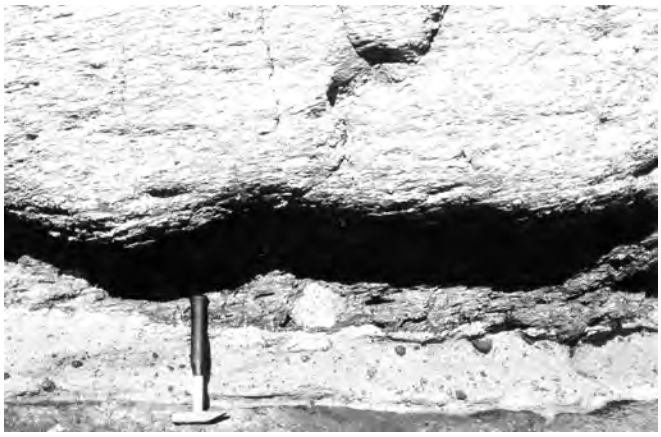

Figure 10. Basal zone of Mogán D ignimbrite, wave-cut platform on west side of the mouth of Barranco de los Frailes. The basal unit is around 200mm thick, now represented by a yellow-green clay band that is eroded more easily compared to the overlying intensely welded zone.

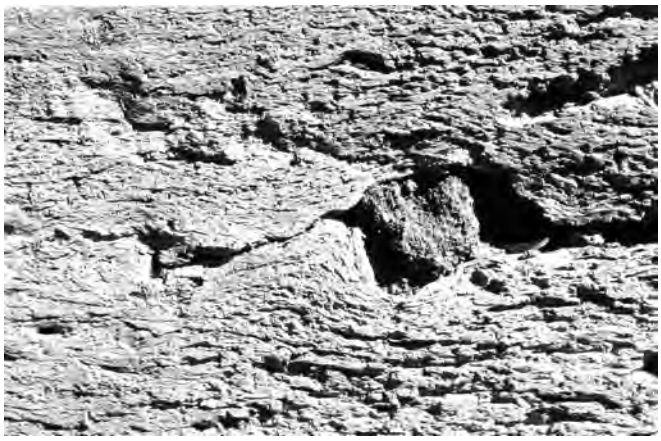

Figure 11. Rotated lithic clast with asymmetric pressure shadows preserved as cavities on either side of the clast. Lower welded zone of Mogán D ignimbrite, west side of Barranco de los Frailes. Lithic clast *c.* 50mm in diameter. Shear sense top to right; cf Schmincke H-U & Swanson DA, 1967, Plate 3B.

Figure 12. Strongly welded fabric that shows principally symmetric features, suggesting that this zone responded principally by flattening in response to the overlying load. Middle welded zone of Mogán D ignimbrite, west side of Barranco de los Frailes. Field of view *c.* 200mm by 300mm.

Figure 13. Unwelded fabric containing unflattened pumice fragments in a random orientation. Upper unwelded zone of Mogán D ignimbrite, west side of Barranco de los Frailes. Section at right angles to foliation in lower,welded units. Diameter of coin 20mm.

iv) An upper zone that becomes progressively less welded upwards. The upper unwelded zone contains unflattened pumice fragments in a random orientation (Figure 13).

Mogán Formation, Unit E

Unit E is the uppermost cooling unit in the Mogán Formation. It has a conspicuous chemical zonation (Figure 14) with a lower light coloured comenditic zone and an upper greyish trachytic zone that are sometimes separated by a hybrid zone (Leat & Schmincke, 1993). Table 2 summarises the principal features of unit E.

Table 2: Principal features of Unit E, Mogán Formation

Zone	Composition	Description
ET	trachytic	Lower part welded with blue-grey colour; top unwelded and usually reddish colour
EM	mixed	Mixed zone of variable thickness, typically 1m thick
EC	comenditic	Light colour, intensely welded everywhere. Fiamme-rich, lithic-poor. Glassy chilled margin at base

Ignimbrite E is distinctive in outcrop with white, blue-grey and reddish bands that can often be seen to run for kilometres along the sides of barranco walls: it thus acts as a useful marker horizon. However in places this simple stratigraphy becomes disrupted by large scale rheomorphic features as described below.

Ignimbrite E exhibits rheomorphic deformation features at all scales from microscopic through to structures that are hundreds of metres long. The chemical zonation of Unit E is the key to understanding the deformation behaviour. While the upper trachytic ET zone tended to behave in a brittle manner, the lower comenditic EC zone shows widespread evidence of ductile deformation. Small scale indicators of ductile deformation include:

i) Extreme flattening of pumice clasts, visible in sections at right angles to the foliation (Figure 15)

Figure 14. Junction between the lower light coloured comenditic zone (EC) and the upper greyish trachytic zone (ET) of the Mogán E ignimbrite unit. Location adjacent to SE end of Tiritaña road tunnel (GC500).

Figure 15. Extreme flattening of pumice clasts. Lower comenditic zone (EC) of Mogán E ignimbrite, west side of Barranco de los Frailes. Field of view *c.* 700mm by 1m. The large pumice fragment just below the centre has developed tension cracks in response to shear stresses that developed during flow of the surrounding, more ductile matrix; cf Schmincke H-U & Swanson DA, 1967, Figure 6.

Figure 16. Pulled apart pumice fragments. Lower comenditic zone (EC) of Mogán E ignimbrite, west side of Barranco de los Frailes. Field of view *c.* 200mm by 300mm. Here the fractured segments of pumice have been variably rotated and separated, with the intervening gaps infilled by matrix material.

Figure 17. Flow folding developed in EC zone of Mogán E ignimbrite. Location adjacent to SE end of Tiritaña road tunnel (GC500). Diameter of coin 20mm.

Figure 18. Flow folding developed in EC zone of Mogán E ignimbrite. Location as per Figure 17. Field of view *c*. 200mm by 300mm. Note the prominent minor "Z" folds on the left-hand limb of the main antiform.

Figure 19. Large scale deformation within the Mogán E ignimbrite, with a highly irregular contact between the lower EC and the upper ET. Road cut adjacent to NW end of Tiritaña road tunnel (GC500).
Vertical scale *c*. 30m.

Figure 20. Part of a block of trachytic (ET) ignimbrite surrounded by deformed comenditic (EC) ignimbrite. Mogán E ignimbrite, road cut on Puerto de Mogán – Veneguera road (see Figure 6). Vertical scale *c*. 2m. Note that the foliation in EC is contact-parallel, emphasising the much more fluid nature of EC compared with ET.

ii) Pulled apart pumice fragments; where the pumice clasts have undergone an initial ductile deformation followed by a brittle deformation induced by shear stresses developed within the surrounding, more ductile matrix. These pumice fragments can develop tension cracks (Figure 15) ; ultimately the resulting segments separate, with the intervening gaps infilled by matrix material (Figure 16).

iii) Flow folding (Figures 17 & 18).

As well as small-scale deformation structures, rheomorphic deformation may produce structures that are hundreds of metres long (Leat & Schmincke 1993). At some localities it is possible to observe, for example, white EC overlying grey ET or grey ET lying directly on the unwelded top of the previous (Mogán D) cooling unit. Figure 19 shows an example of large scale deformation, with a highly irregular contact between the lower EC and the upper ET. Figure 20 shows part of a block of ET surrounded by deformed EC, where the foliation in EC is contact-parallel, emphasising the much more fluid nature of EC compared with ET. Figure 21 (adapted from Leat & Schmincke, 1993) presents a synthesis of a number of these larger scale deformation structures.

Summary

A sequence of volcanic rocks, principally welded ignimbrites with subsidiary lava flows, is exposed in the arid coastal zone of SW Gran Canaria. Within this sequence, a group of peralkaline, rhyolitic ignimbrites was sufficiently mobile to undergo rheomorphic deformation. The exposures exhibit deformation features on scales ranging from microscopic to hundreds of metres long. This location thus represents an area of outstanding geological interest.

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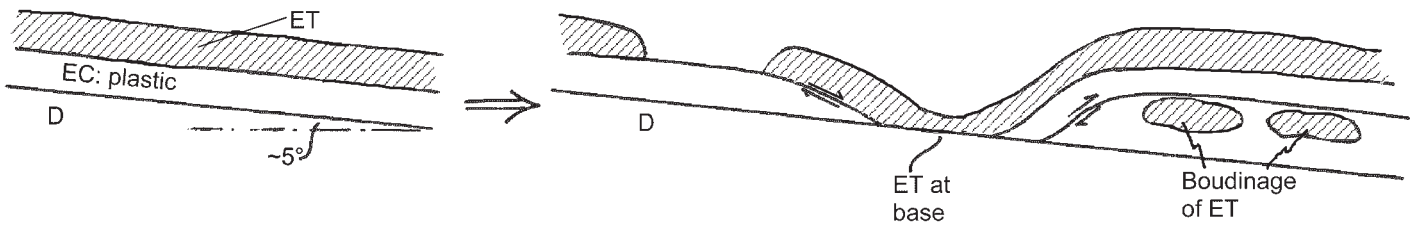

Figure 21: Synthesis of larger-scale deformation structures within the Mogán E ignimbrite.

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Book reviews

Impossible Extinction - natural catastrophes and the supremacy of the microbial world by Charles S Cockell, 2003, Cambridge University Press, 181 pages, £18.95 (hardback) ISBN 0521817366.

The title of this slim book caught my eye, then I read the cover blurb andwas intrigued. It added another physical cycle to Milankovitch's list :the Solar System's 225-million-year rotation around the Milky Way galaxy.

Earth's geological history since the end of the Permian (when we werelast in our current galactic position) is reviewed, noting the early emergence of micro-organisms, the main climatic and tectonic changes andmajor impact events.

Over recent decades, of course, the surface of our planet has been scoured for evidence of impact craters and one has been identified in Northern Canada, named Haughton after the local river. The crater is 24km across and was created 23Ma ago on a remote arctic island at 75°N. Since 1997 NASA has organised summer expeditions to investigate the site and Charles Cockell (a microbiologist with the British Antarctic Survey) participated. Though life was devastated here at the time of the impact he found that cyanobacteria had recolonised fissures in the shocked and bleached gneiss debris and were thriving on, in and under the rocks. Microbe-rich sediments, formed in a now-depleted crater lake, support arctic grasses, foxes, musk ox and arctic owls so that the crater is now "a wonderful and luxuriant expanse of green against the lifeless grey and brown of the polar desert".

The author has a passion for micro-organisms and their variety and tenacity in surviving extreme environments: "11km deep in the oceans ... 3km deep in ice ... 5.5km deep in rocks ... 70km high in the atmosphere" and everywhere else in between. He discusses the ranges of temperature, pressure and pH, and levels of water and oxygen where these tiny organisms have been found living. Then Cockell tells how microbes have been conscripted to clean up the polluting consequences of mankind's "intelligent stupidity" and ponders their potential in space.

This slim book focuses on the huge subject of the smallest life-forms found on Earth. Inspirational for anyone considering the possibility of life out there, Earth scientists will enjoy Cockell's infectious (!) enthusiasm for microbes as an apparently Impossible Extinction.

Sybil Richardson BA(Hons)Open and an OU 'lifelong learner'.

Petroleum Geoscience by Jon Gluyas and Richard Swarbrick, 2004, Blackwell Science, 359pp, £37.50 paperback, ISBN 0632037679

This book is intended as an introduction to petroleum geoscience. It is aimed at geological undergraduates in the latter years of the course, postgraduates and non-geologists in the petroleum industry. The text is dense with information and the illustrations are monochromatic, but these qualities do not detract from the book's value to those with a sound foundation in geology. That being said it is likely that someone coming from a background of engineering or environmental science (a group at which the book is also aimed) would have some difficulty to come up to speed in basin analysis and stratigraphy if they relied solely on this text. However, to be fair the authors clearly state that these aspects are not covered in great detail and there are suggestions for further reading.

Chapters 1 and 2 are largely introductory and deal with terminology and concepts particular to petroleum geoscience. Chapter 2 which is on Tools is comprehensive but, of necessity due to limited space, not detailed and I was pleased to have had the advantage of having completed S338 before reading it.

Chapters 3 to 6 lead the reader rapidly through the politics of decision making and licensing into the technicalities that determine Exploration, Exploitation, Appraisal, Development and Production. These latter chapters also contain sixteen case histories of exploration throughout the world including seven from the UK. I found these of particular interest and value since they demonstrate the integration of petroleum geotechnology and academic geology.

For geology graduates considering a career in the petroleum industry or related research this is a valuable introductory text.

Tony Milward FGS, Continuing OU Earth Science Student

Theory as to possible local contributory cause of the Manchester earthquake swarm October/November 2002

Peter Gavagan BSc (Hons)

Like many residents of the Greater Manchester area, I was a keen follower of the news about the swarm of earth tremors which hit the Manchester area between the 21st October and the 13th November 2002. During that period the British Geological Survey recorded some 99 tremors, ranging in intensity from 1.1 to 3.9 on the Richter scale, with the two strongest tremors with intensities of 3.5 and 3.9 both being recorded at the outset, on the 21st October at 11.42.

In the immediate aftermath of the initial tremors, Manchester University published some useful information about the proximity of various major faults and indicated what monitoring was taking place, but once the initial public interest subsided, nothing further appears to have been published on the subject.

In addition to the obvious global tectonic factors at work as the cause behind the Manchester earthquake swarm, namely the stresses generated as a result of the continuing spread of the Earth's crust away from the Mid-Atlantic Ridge interacting with further stresses generated by the Northward drift of the African Continental plate towards Europe; it is also suggested that we should take a serious look at a possible more proximal cause: water.

It is an established fact in geological circles that most earthquakes occur in the uppermost parts of the crust and are the result of brittle failure and frictional sliding. It is also accepted that elevated pore-fluid pressure can be a major contributory factor in the propagation of brittle rock failure, leading to earthquakes. i.e. when sedimentary rocks, such as those found in the Coal Measures, are subjected to great pressures from overburden, and water within the pore spaces within the rock is forced out, the rock is much less susceptible to break easily. When such rocks come into contact with water, their internal pore fluid pressures increase, and the rock becomes much more susceptible to brittle failure, which is what normally causes the release of energy in an earthquake. Water flowing along established faults will also provide mechanical lubrication in the event of movement occurring on such a fault.

This is such a well-established fact concerning the way that brittle failure occurs in rocks, that in areas prone to earth tremors which are likely to cause substantial damage (e.g. in California, on the San Andreas Fault), water has even been pumped into major faults at high pressure via deep boreholes, causing earthquakes and releasing pent-up energy in a series of smaller tremors thereby avoiding a sudden high-energy tremor with its associated structural damage.

So there is a direct relationship between the presence of water, particularly under high pressure on or near to an established active fault, and the resulting release of energy via earthquakes.

Living just to the North of Manchester, the writer is only too well-aware of the recent elevated levels of rainfall in the area to the North of the Pendleton fault, which has been so great on occasions as to lead to flash-flooding sufficient to move tens of tons of rock debris in streams draining the local moorland, occasionally within the space of a couple of hours. This must have led to a substantial increase in the volume of water finding its way into the sub-surface.

Geological investigations to date into the origins of the current Manchester swarm indicate that movement on the Pendleton Fault is the prime suspect (Figure 1). What may not be apparent to people living outside the Manchester area is that the site of the former Agecroft Colliery in Salford, which ceased production about twelve years ago, lies at the northern end of the Pendleton Fault. Whilst the mine was still active the groundwaters flowing into the workings were pumped out on a regular basis, which is no longer happening. In addition to the deep and extensive Agecroft workings, there may well be other flooded and abandoned former coal workings in the north and east Manchester

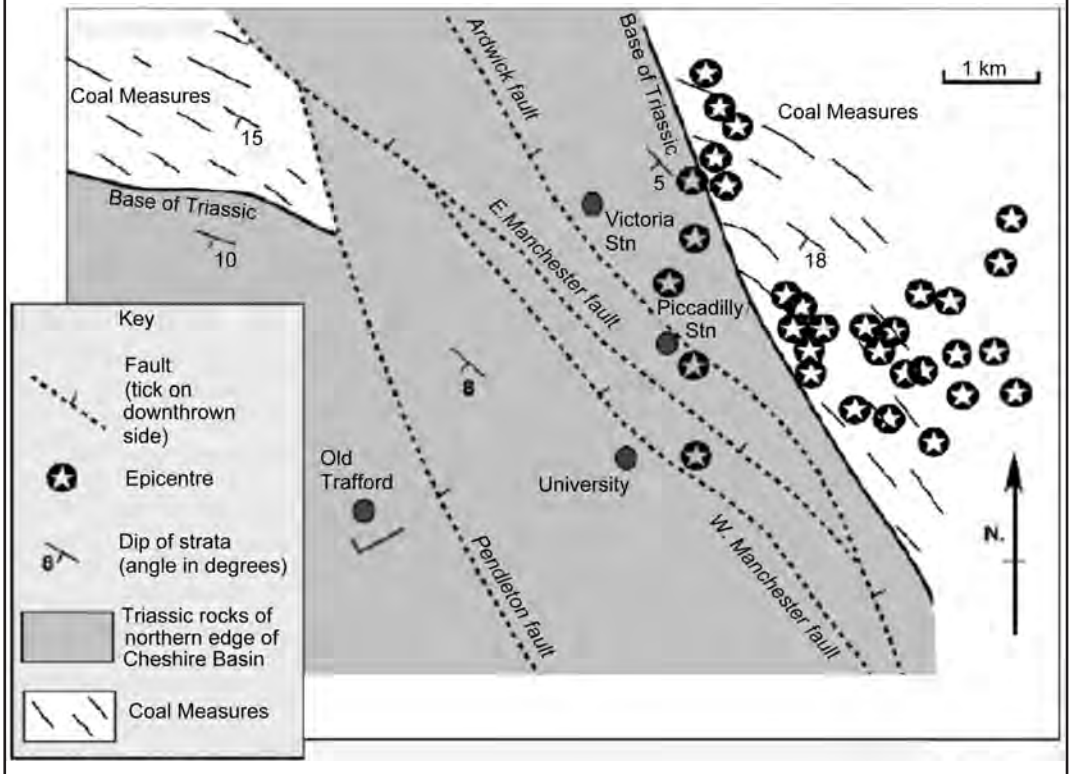

Figure 1. Geological map of Manchester City area showing epicentres and faults. Geological information abstracted and simplified from BGS 1:50000 Geological Sheet 85, Manchester.

areas, which may possibly be proximal to, or even intersect, the various faults close to which tremors have occurred. The Manchester University Department of Earth Science's web pages on the subject of the Manchester earthquakes also mention former mine-workings in the Patricroft and Bradford Districts of Manchester; the latter site lying on the east side of Manchester in close proximity to the presumed epicentres of most of the tremors.

Several years ago the writer had a conversation with a journalist who had had the opportunity to go underground at Agecroft while it was still operating; not only did the main shaft go very deep, but at the foot of the shaft there was a very steep slope leading down to even deeper levels in the Coal Measures. It is not unreasonable to assume that these galleries are now well and truly flooded and constitute huge underground reservoirs in close proximity to the Pendleton Fault. There is recent anecdotal evidence to the effect that, since the closure of Agecroft Colliery and the cessation of pumping, residents in the Worsley area have been aware of a rise in the local water table.

A local journalist produced some archive material relating to the opening of the Agecroft Colliery in the early 1960s. It was interesting to read how miners, arriving at that particular pit from other local collieries, were surprised by the amount of water encountered in those workings. It evidently constituted a more significant problem than in other local coal mines, so much so, that Wellingtons were often the preferred footwear, rather than working boots. I was recently informed that pumping from the workings finally ceased about seven years ago, and all traces of the mine overstructure have been removed, along with the huge coal heaps, the adjacent power station and its massive cooling towers. Large areas in the vicinity of where Agecroft colliery and the power station once stood are now occupied by a prison, office developments and housing developments.

On the subject of water levels in adjacent mine workings, there is similar anecdotal evidence available relating to the main shaft of the New Earth Colliery at Clifton further up the Croal-Irwell Valley and on the line of the Irwell Fault, where coal workings date back to the 18th century. Apparently, several years ago it was some 115m from the top of the shaft down to the surface of the water, whereas now the water level is within 15m of the surface.

If this is the case, then there is a constant supply of deep-lying ground-waters available to seep along the course of the Pendleton Fault and/or any neighbouring faults, which could provide the requisite increase in pore-fluid pressure to make brittle-failure at depth all the more likely.

Suggested mechanism at work

It is suggested that in the days when coal was still being mined locally, water finding its way into the mine workings was being pumped out on a regular basis and the workings were simply massive voids in the sub-surface. When mine closures occurred and pumping ceased, local water tables would rise and the massive voids formed by both the shafts and the laterally-extending galleries would gradually flood and form extensive underground reservoirs holding millions of tonnes of water. To the extent that water levels in deep shafts have risen over the years, there will be considerable downward pressures being exerted upon the bodies of water within the galleries at the foot of such shafts. The calculation of such pressures is easily done, using a readily available formula.

However, since water finds its own level, such flooded mine workings will normally be stable, closed, underground reservoir systems, though the presence of large bodies of water in the flooded galleries will have lead to local increases in pore-fluid pressures within the rock units immediately surrounding the workings.

It is proposed that this stability came to an end in late October 2002 in the lead-up to the 3.2 Magnitude,3.9 Magnitude and 3.5 Magnitude tremors on the 21st October 2002. What was a stable, closed system could have become, in effect, a high-pressure hydraulic system, driven by the force exerted by the mass of the water columns in the main vertical shafts. Tremors of this order of magnitude would have been sufficient to open up cracks, fissures and any other areas of subterranean weakness, immediately allowing water from the galleries and shafts to exploit every area of weakness, possibly lubricating fault planes and certainly increasing the area over which pore-fluid pressures would have been raised, thus leading to a rolling swarm of individual brittle rock failure events generating the series of earth tremors which continued unabated from the 21st October to the 13th November. The fact that the magnitudes of the later earth tremors were smaller than those on the 21st October suggests that the increased pore-fluid pressure over a wider area or volume of rock had resulted in a more gradual release of energy as the process progressed. Between the 19th October and the 13th November 2002, there were no fewer than 104 separate earth tremors.

Points raised against such a mechanism being at work fall into two areas. One is the effect of overpressure in strata in which the earthquakes occur which would tend to reduce the capacity of cracks, faults, fissures and pore spaces to permit the transfer of liquids in the sub-surface. However, one should not overlook the fact that the major known faults in the area cut right down through the upper Triassic rock units and down into the Coal Measures. In addition to the known faults, it is highly probable that there are other minor faults in existence, about which we have no knowledge. These would all provide ideal conduits for water to enter and spread within the sub-surface, both from former mine workings and also possibly from surface sources.

Clearly, the issue of connectivity between faults, cracks, joints and fissures is of major importance if the role of water, whether under pressure or not, is to be accepted as being instrumental in allowing the present earthquake swarm to develop in the way that it has done to date. It is suggested that the connectivity would have been very greatly enhanced after the initial major tremors had disturbed the most likely potential routes through which water under pressure could permeate wider areas of the sub-surface, thereby raising pore fluid pressures over an increasingly wide area, leading to a self-propagating scenario of brittle failure at depth and the consequential earth tremors.

In order to test this theory in detail, besides obtaining further and more accurate data as to the locations and depths of the earthquakes, it would be beneficial to try to obtain data relating to Agecroft and any other mine workings which lie within a reasonable distance of the Pendleton, East Manchester, West Manchester and Ardwick Faults. Such details would include the depth and width of the main shafts, the lateral extent of the workings, the heights and widths of the galleries, and the volumes of water which were being pumped out of the workings when they were

still in operation. It would also be useful to know whether there is any current data as to the existing levels of water within the main vertical shafts and whether any of the horizontal workings pass in close proximity to, or intersect, known fault planes.

Perhaps other readers of the Journal may have access to such records and operating details which affected the day-to-day conditions at Agecroft and, if such information can be found, it may be possible to consider this theory of causation in more depth – hopefully with some input from some hydrogeologists!

Author

In childhood Peter Gavagan's interest was aroused whilst collecting Carboniferous fossils from some local shale-heaps. Most of his working life has been spent in the legal/accountancy sphere. In middle age he started an Environmental Science degree at Salford and subsequently transferred to a Geology degree at Manchester where he obtained a BSc (Hons). Although currently employed in legal litigation work he still has an abiding interest in geology.

Book reviews

Beaches and Coasts. Richard A. Davis Jr and Duncan M. Fitzgerald, 2004, Blackwell Publishing, 419pp including Glossary and Index (hardback) £35. ISBN 063204383.

Coasts matter to geologists. They give the stratigrapher and the fossil hunter some of our best and most continuous exposures (vide our 'Jurassic Coast'). For the geomorphologist they are perhaps only second to volcanoes as real-time evolving evidence of 'the present as the key to the past'. As this book also shows, geology and geophysics feed back into the present-day understanding of coastal processes. Coastal processes are vitally important to humans: nearly half the world's population lives within 100km of a coastline. Billions of people are therefore historically, currently, or potentially subject to the benefits and vicissitudes of the dynamic triple junction of earth, air, and water.

After a detailed list of contents, Chapter 1 defines the key objectives of the book:

> "…we consider the controlling factors that determine what type of coast develops. The processes that develop and maintain coastal environments, as well as those that destroy the coast, are discussed in order to convey the dynamic nature of all coastal environments. Each of the major environments is considered in light of these controlling factors and processes. The impact of human activity along the coast has been enormous, especially over the past century. Many examples of this impact appear throughout the book but a special chapter devoted to the topic is also included. Most of the emphasis in the book is directed toward geologic and physical attributes of the coast, although organisms are not overlooked."

The authors do not provide their credentials but I deduce that one or both are associated with the US Army Corps of Engineers, who lead federal responsibility for coastal engineering issues in the USA.

S339 students will find immediate pleasure in Chapter 2, which shows how plate tectonic considerations provide a high-level systematics for the continent-eye view of coastal development. The United States perspective of the book, which is apparent throughout, sees a good fit of the morphology with that country's contrasting East-passive and West-subducting continental margins - less easy for us to apply the concepts to the Atlantic coasts of Europe! The Level 2 geologist will feel at home with Chapter 3, covering the sedimentary materials. Chapter 4 explores the way sea levels respond to past and prospective global climate changes and introduces the human as well as the geologic factors. The contemporary sea level changes are a recurrent theme in the book and I particularly liked the attention given to oceanic thermal expansion, so often forgotten in popular discussion focussed on ice sheets as the primary issue.

Chapter 5 ascends into the third 'element', for the meteorological factors. Those addicted to 'perfect storms' will enjoy this chapter, though the authors' obvious pleasure in the anecdotes still leaves enough space for (US) data and classification schemes. Chapters 6 and 7 are perhaps the best for seaside holiday reading: how nice to lie back on the beach and consider whether 'reflective' or 'dissipative' is the best description for what is going on around you. Chapters 8 and 9 take us into more detailed morphological features, barrier systems and dunes, before introducing tidal theory and effects in the next three Chapters. We are now well into conventional territory for such books: wetlands, estuaries, and deltas follow. Chapter 17 is more novel. It looks not only at the rock sculpturing left by glaciation but also at the significance of the drift as a voluminous coastal source of loose, diverse-sized, and easily eroded sedimentary material.

Rocky coasts (Chapter 18) are, I suspect, too diverse for comprehensive treatment within the intent of this book, and the same problem lurks in Chapter 19's foray into reef biology. With Chapter 20 we are back to more of the real-time drama with erosion, which leads well into the final chapter's specific discussion of human impact. It is a last reminder of a recurring theme: we meddle at our peril!

A good glossary and index complete the book and every chapter concludes with a selective bibliography.

The many photographs, in black-and-white, are sometimes barely big enough for comprehension. Good and frequent diagrams add a helpful blue-grey half-toning but in some graphs axes are not fully labelled. The same blue-grey half-tone is used in pictures forming an underlay to text in the boxes. Unfortunately, the designers fell into the common trap that the underlay, which can only be decorative, is sometimes dark enough to make the print harder to read; I suspect it might be really troublesome for someone who is visually impaired.

I enjoyed reading this book and commend it for pleasurable interest, as well as a reference sourcebook at the level of an introduction to serious practical and academic study.

George Sudbury graduated bachelor in Physics and doctorate in Space Astrophysics 'many years ago' and is a Chartered Engineer. He has completed S236 and S339 and is awaiting the OU Short Course 'Weather and Climate Modelling' as his next challenge.

Fossils at a Glance by Clare Milsom and Sue Rigby, 2004, Blackwell Science Ltd, 155pp, £19.99 (paperback) ISBN 0632060476.

This textbook would be a fine addition to any students Earth Sciences library. The general layout makes the data easily accessible, each topic having its own glossary at the end of the chapter. A comprehensive index aids its use as a reference book. It is well laid out with clear, easy to access tables of information and excellent diagrams.

It starts with an introduction which explains the layout of the book and gives an explanation of the types of fossils their use and limitations. The book includes chapters on invertebrate and vertebrate fossils, microfossils and trace fossils This is followed by chapters on Precambrian and Phanerozoic life.

This book is useful as a reference book or to just pick up and read! It is full of detail and includes a reading list.

Caroline Deans BA Hons (Open) OU Tutor

The Bost Sawmills: far and wide geology from a high geographical point

Rob Heslop

A visit to the Pilat Mountain Park, where the land surface of 700km² holds thirty or so peaks at over 1000m, in which the mountain pine and lowland hornbeam suffer from Mistral winds and hurricanes. I set off to ramble the rugged Pilat Park, and to see the long distance views they contain. Lost in this mixed territory of metamorphic crust, wind and lichens, we find …The Bost Sawmills

'Un café et un croissant, s'il vous plaît', I'm in the motorway garage snack bar, sitting on a tall stool by the counter. At seven in the morning, I'm surrounded by the bustle of a new Monday, lorry drivers, travelling salesmen and hurried secretaries; all enjoying a rushed breakfast, French style.

This is the heart of the narrow Black Valley, the industrial corridor of St. Etienne and St. Chamond, (departement; La Loire). This overcrowded valley is crushed between two, almost uninhabited, natural beauty spots; to the south, La Pilat National Park, (The Pilat Range; the western series of the Massif Central, a metamorphic mountain containing much hercynian granite, Figure 1), and to the immediate north we have the Lyonnais mountains, (the northern metamorphic series of the Massif Central).

Leaving the motorway at the bleak town of St. Chamond, I take a small-town road to the Pilat Park boundary.

Gaining altitude, the roads get smaller, the traffic flow thins out. I pass the odd reservoir or two, then drive over an enormous concrete dam, before leaving the road for a narrow bridle track, sign posted '*Le Scie De Bost*'.

The track humps, bends and bumps in a struggle to reach a lonely destination right at the top of a spectacular valley. Huge hills loom on either side. Torrents of wild, angry waters cascade around the bridle-track. Slowly progressing and gaining height, I arrive at the Bost Mills and hamlet and park near a rounded pile of a hundred and one pine logs.

Figure 1. The early geographers Cassini and son mapped parts of France in the 1760s. Here we have La Pilat, with Bost, left of centre. (Reproduced with kind permission of *La Jasserie de Pilat*, Eric Perrin 2003.)

Leaving the car, and setting off in chilly fresh mountain air to the deafening sound of teeming, hurried waters, I pass the Bost Sawmills and dry-stone walled hamlet. In all, there cannot be more than twenty or so farm-folk living in this isolated, harsh place. Originally, a few hundred years ago, Bost would have been a busy, important sawmill, supplying logs and planks to the lowland Black Valley. The great smell of fir and spruce and pine fills the air. A weed-covered track leads on between two abandoned granite-stone farms, and begins an upward ascent.

This is mountain-land; swelled due to Alpine folding during the Miocene, the upheaval of the Pilat Range has, in some places, revealed an ancient stratigraphy showing an older volcanic-sedimentary complex (spilitic-keratophyric).

I pass a pile of freshly amassed, smelly dung, before coming to an old stocky beech (*Fagus syvatica*). This remarkable beech seems to hold the skies aloft with its branches. Fantastic, they stretch, reach, grab and hold precious sunlight. Looking up I stand tiny and alone; the thriving centenarian moves not.

At this point precisely, the track takes a sharp right, and heads upwards and into a forest of amber-coloured hornbeam (*Carpinus betulus*), and Norwegian spruce (*Picea abies*). The colours, the woods and the natural beauty of this area are simply breathtaking.

Walking upon the track of smooth granite slabs, the going becomes exceedingly steep. Round rocks and green, lichen stained boulders are strewn everywhere. The silver hornbeam trunks are also covered in lichens. It would seem to be the perfect environment for them as large, leaf-like lichen (*Foliose*) are thriving on every tree. The lichens are a strange mix of two life systems; fungi and algae. Together they grow as one, each benefiting from the other as a strange and successful symbiotic system. The light becomes gloomy as I go on with the upward struggle. The Norway spruce now dominate; these conifers grow tall and closely together, selfishly blocking out the light. This whole park, from an altitude of around 800m or so, is packed, kilometre after kilometre by these greedy, thin trees. The areas remain blessed, however, by that marvellous pine odour. And thankfully, there are clearings and moorlands for other trees and shrubs to exploit: rowan, beech, hornbeam, hawthorn, Swiss pine and silver fir, and the mountain bilberry (*Vaccinium myrtillus,* Figure 2).

Further on, I hear the sound of rushing waters. The way levels out and passes another old beech tree before arriving at The-Gier-Jumps waterfalls (*le saut de Gier*). This high waterfall steps in three stages, I see two of them. Spitting spray, noisy and violent, these impressive mountain falls were most probably visited by Hadrian, for this is the source of the Gier river, and it was in these areas that Hadrian chan-

Figure 2. Picking the Pilat mountain bilberry in the early 1900s. (Postcard *c.*1900)

nelled the waters, by aquaduct, all the way to Lugdunum (Lyon), 75km away. One can imagine that great emperor, in flowing pageantry, surrounded by generals, guards, scroll holding advisors and 'privileged' slaves. Together, they would all struggle and stumble in the same manner, over the rocks and boulders, and together, they'd all stop and stare in silence at the awesome sight of the incredible 'Gier- Jumps'.

This high waterfall is cradled by treacherous cliffs and crags and steep sloping granite screes (*chirats**). Spruce, and silver fir (*Abies alba*) grow in clefts and crevices.

After seeing the thunderous falls, I retrace my steps a hundred metres or so, return to the beech and, following a sign for the solitary *Jasserie* mountain tavern, head over boulders, tree roots and needle-covered soils upon an almost vertical accent. This is truly a risky climb and requires real physical fitness. Feeling determined and stimulated by the sheer, rugged and gutsy challenge the mountain offers, onwards I go.

During the last few days these areas have been terrorised by that dreadful, maddening wind: The Mistral. A freezing, bitter gale that rages at around midday, calms down evening time, but returns the day after, on and on, for days on end…as I struggle upwards, the spruce canopy starts to sway, swirl, and twist as the Mistral winds slowly return.

An occasional gust gets to ground level; dry humus is scattered; pine trunks creak. A tall, fallen tree blocks the way. I stoop to get by, and am astonished to see others, scattered, toppled, discarded. Giant spruce, hundreds of them, have been up-rooted by the hurricane storms of '99. A huge patch of forest is down and out, trunks pile upon each other, with only the odd specimen still standing … these terrified solitary survivors look shocked.

The dreadful winds that ripped this land apart gusted at almost 200km/h. The winds downed the entire south side of the mountain, the ecosystem was destroyed, and in places the ancient forest consequently died, for six years on, no new young saplings grow, even the mosses and lichens have moved on; it would seem as if Nature has given up and gone to live elsewhere.

The forest tracks are now being re-opened, and over-hanging trees are being cut by lumberjack teams. I count the rings of one newly-sawn spruce, 80-odd lines show 80-odd years of timely, regular seasons. Are hurricane death-winds such as those that crashed through on the natural agenda?

Only with effort can one progress; the track is hardly visible, and at regular intervals logs, stumps, and entire trees block and hinder. Nevertheless, the track goes on by twisting through, along, up and around. In the meantime, the Mistral gales are back with force; I hear the fresh winds whilst walking through the devastated massacre of a windswept battlefield. Sight and sound as a reminder of what may be. Whilst averting stumps and logs, I'm buffeted and pushed by the odd gust. Fearing impending doom, I hurry on! At one point the forest returns to all its splendour, the trees are healthy and undamaged. The mosses, lichens and bilberry thrive, I hear a distant cuckoo, and then see a soaring buzzard, way up high. All as one for natural harmony. But again, a few hundred metres on, there's another completely up-rooted patch. This pattern remains all the way to the Pilat's summit.

The natural spread of pine thins out, the steep climb flattens off; dwarf hornbeam return as I near the high, rugged and wet moorlands of *la pilat* tops. I find the barren flats of another ecosystem.

Vast, pale green grasslands and open moors spread before me. Now out of the pine forests, I feel the evil, wretched, north-westerlies of Mistral, no longer as the odd blustery vortex, but now as a constant gale-force. Ahead I see '*La Jasserie*' mountain tavern (Figure 3).

Figure 3. La Jasserie, near La Pilats summit. Snow covered for skiing in 1909. (Postcard 1909)

Dating from the 18th century, this was the lonely Pilat refuge, comprising of farm, house-stead, and chapel bell-tower. During the long sub-zero snowy winters, the bells would ring, guiding any lost souls to fireside broth and warm bedding. The austere granite building stands exposed upon the moonscape moors of more than 1400 metres altitude. *L'ambiance* will never change. The place will always courageously face the six months long winters that endure here, and will regularly be blasted and beaten by the forceful winds of North and South.

Plodding on against the gales, I cross flat moorlands of soggy grasses, brown budding heather (*Erica carnea*), sprouting wild crocus (*Crocus biflorus*) and even wild, miniature daffodils (*Narcissus*).

Thankful to get to *La Jasserie's* doors, unscathed and hungry, I step in and take a place on a long wooden table by the roaring fireside. Occasionally, bellowing wafts of smoke overflow, and choke-back into the large room. The fumes circle about, before engulfing a group of fresh sausages hanging from the ceiling. A young waitress shows me '*La menu de la Jasserie*'. I greedily select a whacker of a mountain meal, including hams and wild morel mushrooms with kernel and pepper sauce, together with a

glass of St. Joseph red wine … followed by a great selection of goats cheeses. Outside the winds howl. This is truly Great Refuge. A tavern where paupers can feast like kings! *Gastronomy à la Française, c'est ça la vie!*

Heading off once more, I follow frozen paths to La Crest de la Perdrix summit, (1460m) (Figure 4). Passing an occasional stunted pine (*Pinus cembra*), I go on. These resistant, high altitude conifers may well be of a certain age but they remain small and stunted due to the constant harsh climes. They choke with lichens and twist agonisingly through continual freezes often to –20°C. There are also scattered, suffering hornbeam.

I see the Perdrix, a cairn, topped with an orientation table. To reach it, a traverse of a million and one lichen-covered granite boulders. The whole area has an eerie, fluorescent green glow. The lichens thrive, despite the constant colds, as this mountain belongs to them; The Great Lichens glory in every niche.

I scramble, slip, stumble and stride over wretched boulders. Slowly but surely I arrive at the very top of the Pilat Park. At the orientation monument, I gaze around. The views are simply astounding. Starting from the south, the Ardèche National Park, mountains and hills upon a never ending blue wavy landscape. Beyond Ardèche, the Cevennes National Park. To the southwest, the Massif Central, west for the Mounts du Forez, behind them the vast Mounts d'Auvergne. Northwest to the Mounts Roannais, north for the Mounts de Lyon, northeast we find La Jura. To the east for the Dauphine Alps, then behind them, the French Alps; and way beyond them I see the Swiss (Pennine) Alps. Further south for the snowy Vercors National Park. And I pick out the following peaks: Mount Lozere, 1630m (an arid, steep land of mostly mica-schist monotony) Mount Mezenc 1740m, Plomb du Cantal 1858m, Le Cezalier 1400m, and then Pierre sur Haut 1640m. Followed by Puy du Sancy 1886m, an ancient volcano and the highest point of the Massif Central. Crest de la Neige, 1718m, a limestone mountain-scape folded during the Tertiary. Further away for Le Cervin, (the Matterhorn), Switzerland, highest mountain in the Pennine Alps, 4477m, carved and sliced to triangular form due to glacier passage.

Le Mont Blanc, highest mountain in Europe, at 4810m. And also Mont Versio, Italy.

And the Mount Ventoux, 1912 m; Ventoux, meaning Vent, wind. Yet another windy mountain, haunted by that magistral Mistral, formed mostly of Apatien limestone. Olive trees thrive at the base of *Mont Ventoux en Provence...*I see these sentinels through the wind, forever a world apart; altogether comprising more than a quarter of the ground surface of France. These lands are truly grand. La Pilat is a place of fabulous sunrises, and a place of fantastic sunsets. And camping up here, on long hot August nights, means also an ideal site for stargazing.

I leave, take to the forests, and return upon the tracks; downwards to the Bost Mills.

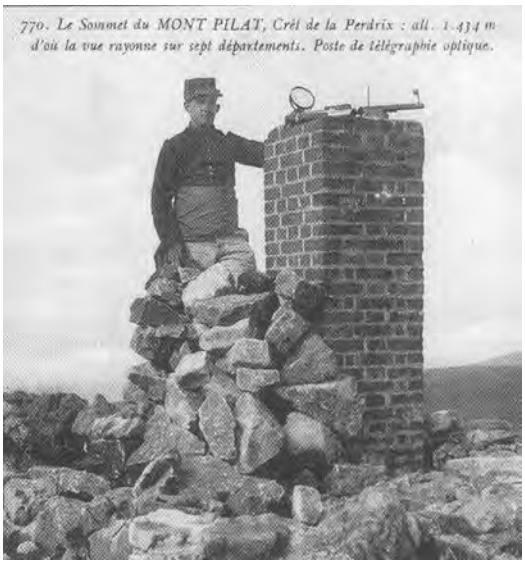
770. Le Sommet du MONT PILAT, Crêt de la Perdrix : alt. 1.434 m
d'où la vue rayonne sur sept départements. Poste de télégraphie optique.

Figure 4.The old cairn of Perdrix topped with a military telescope. Seven French departments can be seen from this point. (Postcard *c.* 1900)

***The Chirats of the Pilat Range**

The Pilat Range is renowned for steep-gradient granite rock.

Periglacial erosion has worn many of the local cliff faces, causing spectacular landslides comprising gigantic sharp boulders and stone; few and far between are the spruce and bilberry that manage to grow in these vast tracts of near-vertical wasteland. Many of the 'screes of chirat' bear witness to the eroding colder climes of the ice ages, but others may well have tumbled due to more recent earth tremors, possibly from the nearby Alpine fault line at Belledonne.

Imagine the noise … lost somewhere in the still and Eden-forest of tranquillity, the splintering, splitting crack of rock-base, echoing like gunfire and followed by a violent and thundering tumble as hundreds of thousands of tonnes of fragmented chunky granite rush and scramble to the hapless valleys way, way down below. The settling of dust pacifies the angry young mountain, and silence returns for a millennium.

Author

Originally from Northumberland, Rob left the UK almost 20 years ago and has since resided in France. He lives with Anne, a musician and has 3 children; Laura 14, Kevin 12 and Matty 2. Palaeontology, Archaeology, Prehistory, wilderness and landscape are the source of much of his work. He is now compiling *The Land-Trek Series. Exploring the Landscapes of France*. Find other articles by Rob on the Mainland Europe website at `http://users.skynet.be.ougseurope/`
at the 'Rock On' index.
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Geological observations in the Dinantian rocks of the South Pembrokeshire coastline

John Downes

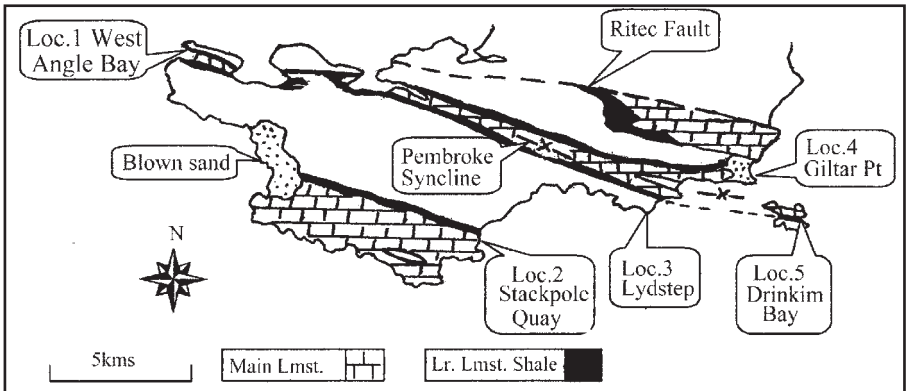

Figure 1. Dinantian outcrops in South Pembrokeshire.

This article describes some of the geological features that can be seen in the Carboniferous rocks of Dinantian age which are exposed on the coast between West Angle Bay, Lydstep and Caldey Island in South Pembrokeshire (Figure 1). Although many of these localities have been researched in detail (see bibliography) the following observations have been recorded in the field and should help to make the rock structures more readily recognizable and understandable to visitors following the coastal path in this part of the Pembrokeshire National Park. All the fold and fault structures are related to the Variscan orogenic movements which are most pronounced south of the Ritec Fault. A stratigraphical column for the Dinantian strata in South Pembrokeshire is shown in Figure 8 at the end of this article.

1.**West Angle Bay** (SM855033) can be approached through the village of Angle; there is a carpark adjacent to the beach. A synclinal axis trends WNW-ESE through the centre of the bay (Figure 3). The Lower Limestone Shales (*Cleistopora* zone) outcrop on either side of the bay with the Main Limestone (*Zaphrentis* zone) occupying the central axial zone. At low tide it is possible to walk along the foreshore and examine the small coves (1-4) on the north side of the bay. Beginning on the eastern side of Cove 1, a small anticline in the Main Limestone displays spaced cleavage, giving rise to bedding/cleavage lineation parallel to the fold axis. On the south side of the cove a thrust fault can be seen running parallel to the main fold axis and thrusting the Lower Limestone shales northwards over the Main Limestone. The line of the thrust can be traced through Cove 2 and into the south side of Cove 3 (Figure 2). A narrow zone of mylonized limestone marks the footwall of the thrust and this can best be seen on the SW side of Cove 2. Mylonite is a fine-grained recrystallised foliated rock which is produced along a thrust zone. On the north side of Cove 2 the Main Limestone is gently folded along an E-W axis and cut by a series of en echelon calcite veins marking small shear zones. Considerable distortion and slumping occurs in the steep back wall of the cove, where a distinctive nodular limestone is exposed. Walk over to the west-facing Cove 3 where a well developed complementary anticline and syncline can be seen plunging ESE. Pressure solution is demonstrated by stylolites on some bedding planes and numerous sinuous calcite veins cut the limestones. Cross over into Cove 4 through the gap in the steep rock wall formed by the vertically bedded Lower Limestone shales. Alternative access to the cove can be achieved by climbing down the steep and narrow path that leads off the coastal track. Proceed to the northern cliff face of the cove which leads round to Thorn Island. There are excellent slickensides preserved in calcite on the folded bedding planes where flexural slippage has occurred. The dip here is approximately 70°SSW. Marked axial planar cleavage can be seen cut by thin sandstone bands indicating the original bedding. A distinctive deformed sediment horizon in steeply dipping strata occurs on the western end of the cliff face at SM851036. Deformation features include a series of truncated minor folds and slump structures. These are found in a lithology of fine-grained micritic limestone (calcilutite) which is sandwiched between limestone layers that show incipient boudinage. Both the upper and lower surfaces of the deformed bed are erosional. There is also a prominent metre-thick bed of concretionary calcareous sandstone (calcarenite)

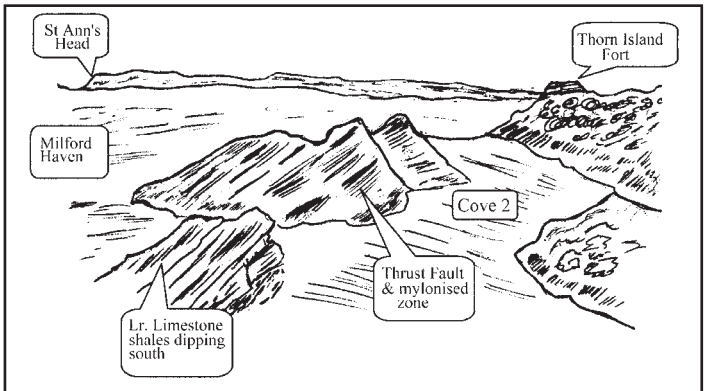

Figure 2. North side of West Angle Bay view looking west.

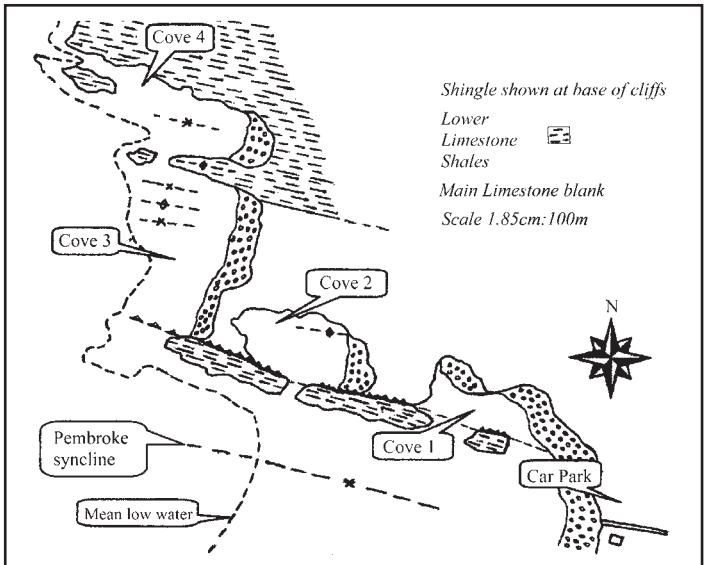

Figure 3. West Angle Bay north side.

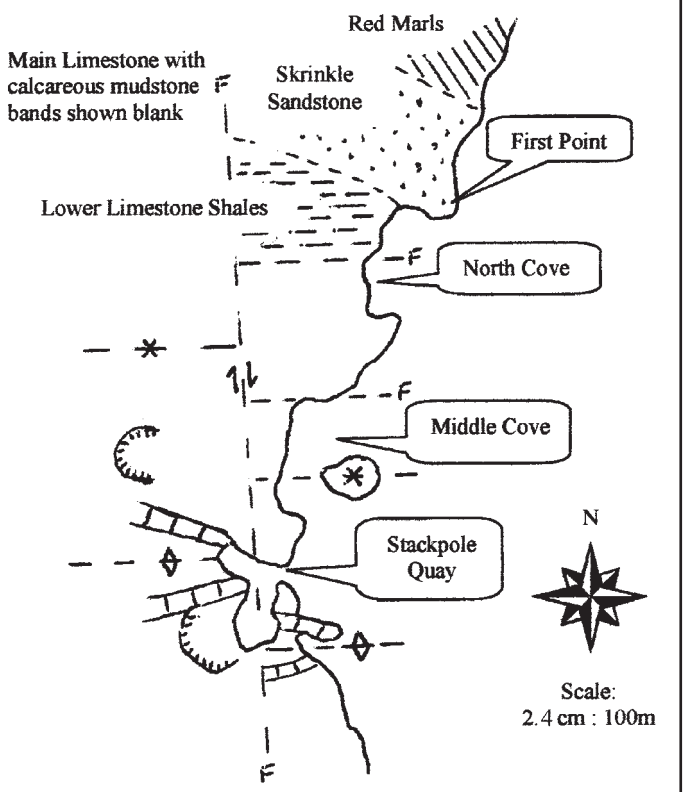

Figure 4. Geology of the coast near Stackpole Quay.

overlying the upper boudinaged limestone. The deformed sequence here can be correlated with the outcrop of the Lower Limestone shales in Drinkim Bay on Caldey Island (Location 5).

2. **Stackpole Quay** (SR994958) is located on the south coast and can be reached from Stackpole village via a narrow lane leading to the National Trust carpark just above the quay (Figure 4). Variscan folding in the Carboniferous Limestone is very much in evidence. The small harbour is eroded into the nose of an eastward plunging anticline, the core of which is exposed in soft calcareous mudstones. The Stackpole tear fault orientated north-south has displaced the fold axis 100 metres to the south. The line of the fracture can clearly be seen on the north side of Stackpole harbour where mudstones on the west are faulted against crinoidal limestones to the east. A synclinal fold axis runs through the small island in Middle Cove where the structure is well displayed, and this axis is also offset dextrally by the Stackpole tear fault. On the north side of Middle Cove, Variscan thrust faulting can be detected at the base of the cliff where the limestone is seen to be overturned at 95°. The limestones on the south side of the cove belong to the Upper *Caninia* Zone (Visean) and contain excellent well preserved silicified specimens of the single coral *Caninia gigantia* and the colonial coral *Lithostrotion*. Walk over the headland to North Cove where the junction between the Lower Limestone Shales and the Skrinkle Sandstones (Upper ORS) can be observed. Access to North Cove is difficult from the coast path, but it is possible to walk over the foreshore at low tide and gain entry to the cove. The basal beds of the Lower Limestone shale contain crinoid debris, siltstone pellets and quartz granules some of which are derived from the siltstones of the underlying Skrinkle beds.

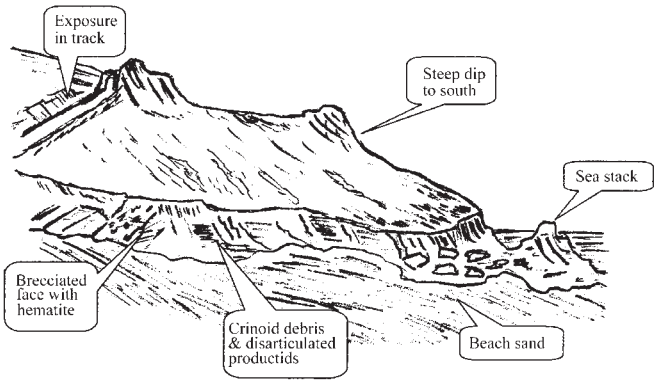

Figure 5. Barafundle Bay northern side.

Return to Stackpole Quay and walk south over the headland to Barafundle Bay (Figure 5). Here a synclinal axis runs E–W through the centre of the bay. The limestone outcropping on the north side of the bay is again in the Upper *Caninia* Zone, but here it contains numerous examples of brachiopods including the productids (e.g. *Delepinea*) and spirifers; zaphrentiod corals are also relatively common. The bedding planes dip steeply south and many faces are composed of crinoidal debris. Evidence of Variscan movement can be seen in the exposures of haematite stained breccia; there are also numerous calcite filled gash veins associated with fold movement. In the side of the track leading up to the archway disarticulated brachiopod shells can be seen scattered through a metre-thick bed of micritic limestone (calcareous mudstone).

3. **Lydstep Point** [SS094975] can be approached from the village of Lydstep down a narrow lane to the National Trust carpark on the headland. However, it is advisable to examine the coast immediately west of Lydstep Point first, so one should take the B4585 road (off the A4139) to the married quarters of Manobier army camp, then follow the military road to the army ranges and the modernistic Youth Hostel building on the cliff top where there is a picnic site and carpark (SS081976). One can first view Skrinkle Haven from the cliff top before climbing down 160 steps to the small cove known as Church Doors, where a magnificent natural arch can be seen in the vertically bedded Church Doors Limestone (*Zaphrentis* Zone). The Lower Limestone Shales (*Cleistopora* Zone) may be examined at beach level where they consist of a series of calcareous sandstones and shales which are almost vertically bedded with a strike direction approximately E-W. It is possible to determine the way up of the beds from the sedimentary structures present. Grain size can be seen to be fining upwards in several of the beds, from a shell horizon at the base through to finer mudstones above. The underlying Skrinkle Sandstones (Upper ORS) are well exposed in Skrinkle Haven to the south of Church Cove.

Reclimb the steps and follow the coast path north-eastwards towards Skomar Draught, a spectacular inlet developed along a N-S fault. Here the Main Limestone (Upper *Caninia* Zone) is exposed, again steeply bedded and parallel to the beds in Church Doors Cove (Strike105°). However, there is evidence of a large scale debris slide formed of gash breccia on the east side of the inlet. A detailed section through a similar breccia can be seen at the side of the coast path leading down the west side of the valley.

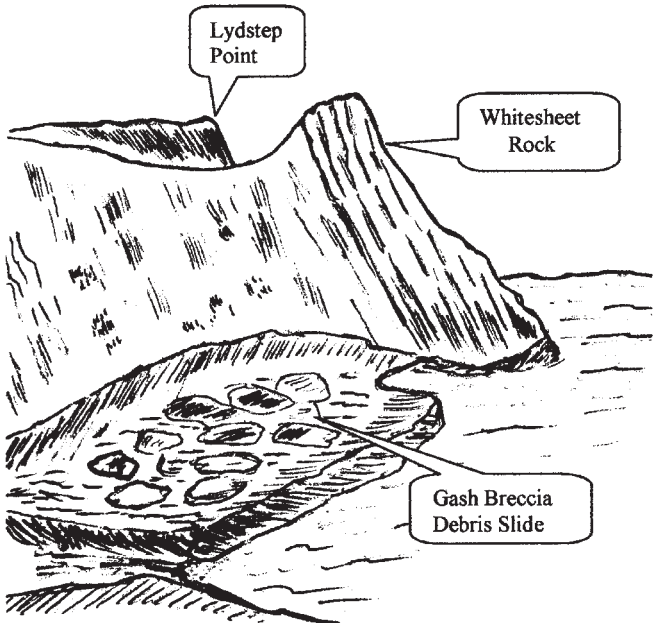

Figure 6. Debris slide at Whitesheet Rock, Lydstep.

Here some limestone clasts are set in a calcite cement, others are set in a sandy matrix. The calcite itself is brecciated as the striations on the crystals are at different angles. There are also many solution cavities where shells have been removed (collapsed breccia?) The origin of this debris slide would appear to be related to wadi infill during Triassic times when torrential floods would have washed boulders and smaller rock fragments down the wadi sides. Continue down to beach level where bedded limestone can be examined on the sides of the deep fault-guided inlet. Climb up to the National Trust carpark on Lydstep headland (SS088978) and proceed along the coast path to Whitesheet Rock where a large area of gash breccia is preserved in an embayment on the foreshore (Figure 6). This debris slide contains limestone clasts up to a metre in diameter often set in a matrix of smaller fragments and Triassic sediment.

4. **Giltar Point, Penally** (SS125983) can be approached from the carpark at Penally railway station. Walk along the footpath over the golf links and the sand dunes to the beach, then take the steep path up to Giltar Point. Note that the headland is part of the military firing range so care must be taken to observe notices and warning flags. About 200m north of the point there is a disused coastal quarry where the Main Limestone can be seen to be dipping strongly to the SE. The view from Giltar Point southwards to Caldey Island looks across the axis of the Pembroke syncline running E-W beneath Caldey Sound. Follow the coast path westwards for about 1.5km to Valleyfield Top. The Main Limestone (Upper *Caninia* Zone) is exposed along the cliffs, dipping steeply south, since here we are on the northern flank of the Pembroke syncline, the centre of which is occupied by Namurian shales which outcrop in Lydstep Bay. Several pockets of gash breccia occur within the limestone along this stretch of coast. A return to the carpark can be made by following the signposted track which runs NE to the A4139 road west of Penally. A small quarry alongside the track at SS113986 exposes the underlying *Zaphrentis* Zone limestones dipping steeply to the SE.

5. **Drinkim Bay, Caldey Island** (SS145963) is reached by ferry from Tenby (summer only) to the landing stage at Priory Bay.

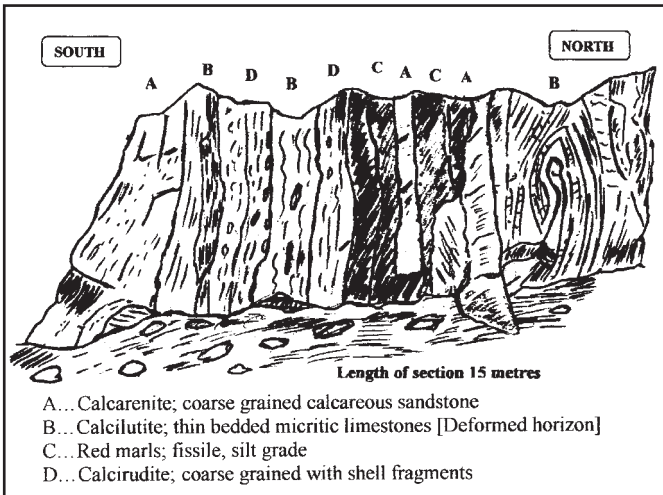
SOUTH
NORTH
A B D B D C A C A B
Length of section 15 metres
A...Calcarenite; coarse grained calcareous sandstone
B...Calcilutite; thin bedded micritic limestones [Deformed horizon]
C...Red marls; fissile, silt grade
D...Calcirudite; coarse grained with shell fragments

Figure 7.Field sketch of deformed sequence at Drinkim Bay, Caldey Island.

Walk up to the road through the village and continue past the monastery towards the lighthouse. At Caldey Priory turn left following the track across the fields to Drinkim Bay. Access to this section is difficult involving a steep descent to beach level via a rope ladder down a narrow gully. For safety reasons this should not be attempted alone. Here the Lower Limestone shales (*Cleistopora* Zone) are exposed in the northern part of the bay; overlying the Skrinkle sandstones (Upper ORS) to the south. The beds are almost vertical and there are several prominent coarse grained calcarenite beds which stand out as rock buttresses. (Figure 7). Deformation structures can be seen in the calcilutite beds which occur in association with fissile red marls and cal-

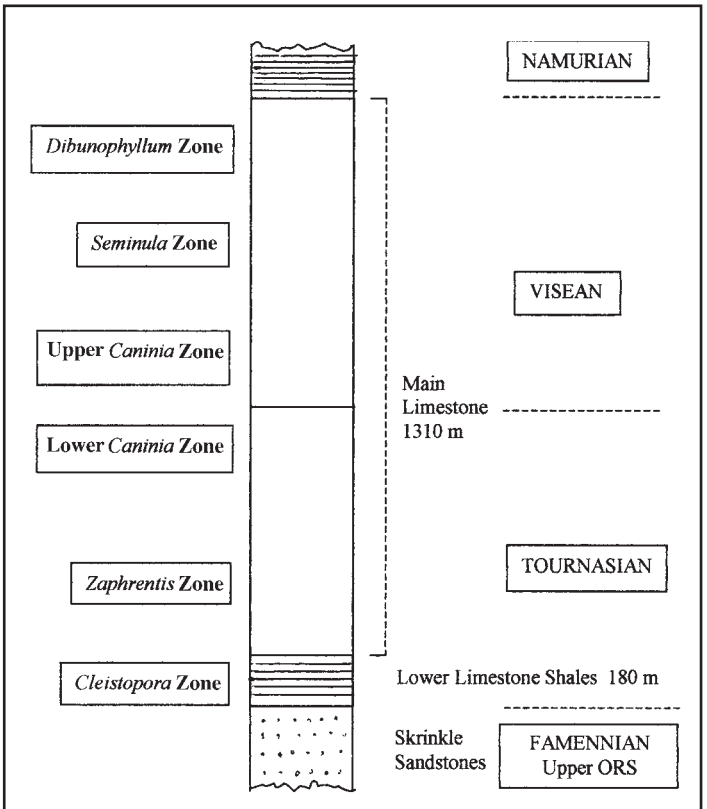

Figure 8. Stratigraphical column for the Dinantian of South Pembrokeshire.

cirudite beds containing shell debris. These minor fold structures appear to represent incompetent sediment deformation during Variscan earth movements. The massive Church Doors Limestone (*Zaphrentis* Zone) is seen dipping at 80°N immediately above the Lower Limestone shale. Note that Caldey Island forms the SE extension of the Pembroke syncline, although only the steep southern flank of the fold is present on the island. In Priory Bay the Main Limestone is actually overturned, dipping at 100°N.

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Maps

British Geological Survey, 1:50,000,Sheet226/227, Milford Haven

British Geological Survey, 1:50,000, Sheet 244/245, Pembroke & Linney Head

Ordnance Survey, 1:25,000, Outdoor Leisure Sheet 36, South Pembrokeshire

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Book revews

Catastrophes and other calamities - the causes of mass extinction by (Anthony) Tony Hallam 2004, Oxford University Press, 246pp, £12.99, (hardback) ISBN 0198524978.

OUP asked Tony Hallam to write a popular account of Mass Extinctions and for this he had two main themes: first to counter the "over-sensationalised treatment by the media" and second, to provide for the general public some idea of how palaeontologists and geologists reach their conclusions.

This is an immediately readable book, full of detail and examples and of a physical size (A5) to make it accessible to most interested people. The informative diagrams are explained fully and add to the textual content. It is book to be carried in the pocket and read whenever there is a little spare time, since most chapters are subdivided and the reader's attention is maintained by various anecdotes and contemporary references. There are comprehensive reading lists, bibliography, glossary and index.

The Preface and first three chapters set out the historical background, changes in thought and various hypotheses, and more modern theories about the reasons for mass extinctions. There is a useful glossary, but usually "new" terms are explained in the text. Reference is made to the papers of Norman Newell published in the 1960s, in which he recognises six Phanerozoic Mass Extinction events. With further research and an enlargement of the "database" Raup & Sepkowski narrowed the major events to five, namely the "end-Ordovician", "late Devonian", "end-Permian", "end-Triassic" and "end-Cretaceous" events, details of which are set out in a comprehensive table. These events became known as the "Big Five" and much of the remainder of the book is based on research into these.

The next five chapters detail the five main possible causes for Mass Extinctions, namely (i) Impact by comets and asteroids, (ii) Sea-level changes, (iii) Oxygen deficiency in the oceans, (iv) Climate change and (v) Volcanic activity. Each cause is examined and explained and reasons given for acceptance or rejection.

The last three chapters (i) pull the strands together, (ii) look at evolutionary significance and (iii) examine the influence of humans.

The first asks whether extinction events were catastrophic or merely calamitous; the culmination of long-lasting minor changes, or short, sharp, shocks; periodic or episodic; affected by wide geographic distribution of species either spatially or latitudinally. In addition the actual physical size and agility of the species may have had an effect. Looking at evolutionary significance, diversity, biotic competition and interaction, food chains and ecological niches are considered.

Finally, the human organism is seen to be the only one having much influence on the biosphere, extinctions and climate change in the Pleistocene.

Rosemary Darby Perpetual OU Student! BSc Hons(Open Earth Sciences), BA(Open), Certs Ed

Geology of the American Southwest: A Journey through Two Billion Years of Plate-Tectonic History by W Scott Baldridge, 2004, Cambridge University Press, 280pp, £19.95 (paperback) ISBN 0521016665, £55.00 (hardback) ISBN 0521816394.

This is a very approachable book, and could be enjoyed by anyone with an interest in geology, although the book is aimed at advanced geology students. The author, a research scientist at Los Alamos National Laboratory, has presented a very comprehensive account of the American Southwest, covering the vast area from West Texas to Southern California, and North Mexico to South Utah; an area with a fascinating geological history.

W Scott Baldridge has successfully brought together items, often seemingly unrelated, of the area's geology and melded them together into a cohesive whole, relating "local geological events to global plate tectonics with episodes of sedimentation, mountain-building and crustal stretching" to cover a time span of two billion years. The author has taken a chronological approach, starting with the formation of the American continental crust and matching subsequent geology from different parts of this vast area. Each chapter is devoted to a particular period of time, with an impressive three chapters to start on the Precambrian alone, and is well laid out with the arguments building clearly and logically.

Although there is an assumption of basic geological knowledge, technical terms are explained clearly in accompanying boxes, and there is a wealth of diagrams and pictures. Unfortunately, the convenient size of the paperback means a lot of page thumbing when referencing diagrams.

Scott Baldridge has effectively summarised much of the research on the area, but does tend to leave the reader to draw their own conclusions, frequently ending sections by suggesting more research is needed.

In summary, this is a good read and sets out what was intended – "a systematic and comprehensive picture of the geology of the southwest since the formation of its earliest rocks in subduction zones, through the formation and fragmentation of at least two and possibly additional supercontinents."

John Lamont, BA Hons (Open), BSc

The geology of Pegwell Bay

Lee Russell

Contemporary setting

Pegwell Bay is situated to the south-west of Ramsgate, on the Isle of Thanet. Until 10,000 years ago the area of the southern North Sea was land (the Dogger Bank, famous for fishing, was an island only about 8,000 years ago). Sea levels rose at the end of the last major glaciation and began to stabilise between 6,000 to 5,000 years ago. When rising waters inundated the land-bridge between Britain and Europe, Thanet eventually became separated from the mainland by the Wantsum Channel.

Around 55-54 BC the Wantsum Channel was a mile or so wide (Butler, Headley & Litten publication date unknown, p61). However, the build up of the 'Stonar Bank' (shingle) at its eastern end and deposition of sediment from the River Stour caused it to silt up and led to its demise. The Stonar Bank advanced northwards and contracted the southern mouth of the channel.

By the fifth century it impeded the flow of the Stour and the Wantsum Channel started to convert to water meadow. Humans then intervened massively in the development of the landscape, reclaiming 16,000 acres in little over 400 years (Cates & Chamberlain 1997, pp14-15). In the 15th century a ferry operated across this channel but by the 16th century it had silted up (Butler, Headley & Litten publication date unknown, p61).

Today the River Wantsum flows from Plucks Gutter (TR 270634), by Sarre (TR 252650) and out to sea near Reculver (TR 245695). Between Plucks Gutter and Pegwell Bay (TR 350634), Thanet is separated from the mainland by the (narrow) River Stour.

A short geological history of Britain and east Kent

Before we look in detail at the geology of Pegwell Bay, it is useful to consider the geological history of the region. Table 1 shows the periods that will be discussed along with a brief description of the conditions prevailing in south-east England and its latitude at those times.

Table 1. Geological periods

Period	Age / Ma	Conditions	Paeleolatitude
Carboniferous	362.5 - 290.0	Land, then low-lying waterlogged plain	Equatorial
Permian	290.0 - 245.0	Non-marine clastic basin	10 to 20°N
Triassic	245.0 - 208.0	Land	
Jurassic	208.0 - 145.6	Land	
Cretaceous	145.6 - 65.0	Land, then marine	45°N
Tertiary	65.0 - 1.64		
Quaternary	1.64 to present		52°N

Through the processes of Plate Tectonics and Continental Drift, what would become south-east England has moved from a latitude of about 60°S at the start of the Ordovician (510 - 439 Ma) to about 52°N today. At various times the region has been land, a low-lying waterlogged plain, part of a marginal marine basin or an emergent beach.

During the Carboniferous Britain was near the equator where, in warm seas and shallow-water, tropical carbonates were being laid down (Toghill 2000, p99). Kent experienced lagoonal conditions followed by a rise in sea-level, yielding a sequence of alternating shales and thin crinoidal marine limestones (Wood, Shephard-Thorn & Harris publication date unknown, p4). Folding and erosion took place during Namurian times (325-315Ma) and no deposits of this age are known from the Wealden area (Gallois 1992, pp7-8). By 315Ma (the Westphalian) there were coal-swamp conditions, with periodic short-lived marine incursions being registered by thin marine bands (Wood, Shephard-Thorn & Harris publication date unknown, p6). In the later Westphalian the area was dominated by clastic sedimentation arising from erosion of the uplifted London-Brabant High to the north (Wood, Shephard-Thorn & Harris publication date unknown, p6; Toghill 2000, p106).

No rocks from the Triassic or Jurassic periods are present in east Kent (including Thanet); presumably it was above sea-level at this time and exposed to sub-aerial erosion. At the end of the Triassic the Tethys Ocean[1] spread over Britain and marine rocks rich in ammonite fossils were laid down. Jurassic Britain was mostly covered by a shallow sea at the margins of the Tethys Ocean, laying down alternations of clays and limestones (Toghill 2000, p131).

By the Cretaceous southern England lay around 45°N. Cretaceous deposition begins with the Lower Greensand and Gault (representing marine transgressions). The Lower Greensand is sandy, with some silts and small amounts of material like chert[2] and ironstone[3] and was laid down in a variety of shallow-water, near-shore environments (Gallois 1992, pp29-30). The Gault is composed of "dark bluish grey to pale grey soft mudstones and silty mudstones". It contains "a rich marine fauna in which molluscs predominate" and "represents an important marine transgression which pushed back the shoreline of the Lower Greensand sea to the borders of Wales and into Northern England" (Gallois 1992, pp35-36). Their marine origin is indicated by their green glauconitic[4] colouration.

The Cretaceous sequence finishes with the Chalk beds (Figure 1). These are massive deposits of biogenic calcite, composed of a coarse fraction of shell debris and foraminifera embedded in a fine matrix of coccoliths (Gallois 1992 p39). The chalk cliffs are folded as part of the Wantsum Syncline which was responsible for separating Thanet from mainland Kent (Thanet Countryside Trust 1986). Examination of the 1:50000 sheet for the area (British Geological Survey, Sheet 274) shows that folding preceded deposition of the Thanet Beds.

In the Tertiary Britain continued to move towards its present location. The climate was often humid and sub-tropical, there may

[1]Tethys Ocean - used to separate Laurasia and Gondwana (the Mediterranean Sea is the last remaining relic of this ocean (see Lapidus & Winstanley 1990)

[2]chert - (flint); siliceous microcrystalline sedimentary rock, mainly of interlocking silica (SiO_2) crystals

[3]ironstone - iron-rich sedimentary rock

[4]Glauconite is considered diagnostic of sediments deposited in a continental shelf marine environment. It is suggestive of slow rates of sediment accumulation and may form by biogenetic or diagenetic alteration of minerals such as biotite or volcanic glass (see internet site http://www.uwrf.edu/~wcø1/glauconite.htm)

Figure 1. Chalk cliffs at Pegwell Bay (Upper Chalk), December 1999.

have been palm trees and crocodiles[5] were common in southern England. Whereas other areas were receiving marine sediments at this time, the Thanet area was mostly a near-shore environment accumulating sandy deposits.

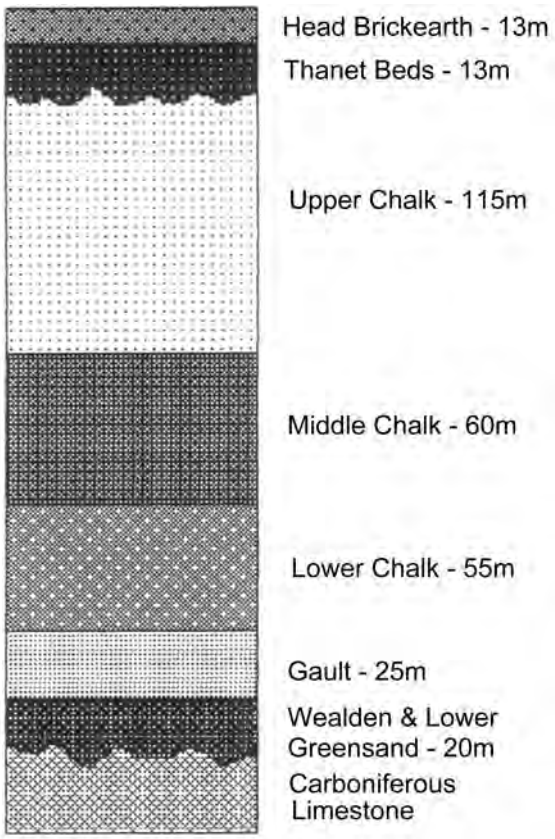


Figure 2. Pegwell Bay vertical section (as derived from the 1:50 000 BGS Sheet 274)

In the Quaternary there has been a cycle of glacial periods interspersed by warmer interglacials. Ice has spread at least four times to temperate latitudes (most recently between about 18,000 and 10,000 years ago) although it has been confined to high latitudes and mountains for about the past 10,000 years (we are currently in a warmer interglacial period). During the last glacial maximum ice cover extended as far south as Essex (Hart, Hindmarsh & Boulton 1990).

The geology at Pegwell Bay

The vertical section in Figure 2 shows the rocks present in the north-east of the bay (these are not all exposed at the surface).

Table 2. The Thanet Beds sequence

e)	**Reculver Silts**
d)	**Pegwell Marls**[6]
c)	**Kentish Sands**
b)	**Stourmouth Clays**
a)	**Bullhead Flint Conglomerate**

The top of the Upper Chalk presents an eroded surface over which the Thanet Beds (about 13m, see Table 2) were deposited. The Kentish Sands are not present at Pegwell Bay; they replace the Pegwell Marls and Reculver Silts in outcrops closer to London.

The Thanet Beds are overlain by the Quaternary Head deposits of the younger Brickearth sequence (about 13m).

Figure 3. The Sub-Eocene Unconformity at Pegwell Bay, December 1999. Above: An exposure of the sub-Eocene unconformity. Below: Close-up of the sub-Eocene unconformity.

[5] As an example, although crocodilian fossils are rare in the London Clay (Eocene period), vertebrae and scutes have been recovered from the Isle of Sheppey, plus exceptionally rare whole skulls.

[6] A marl is a friable mixture of subequal amounts of micrite and clay minerals.

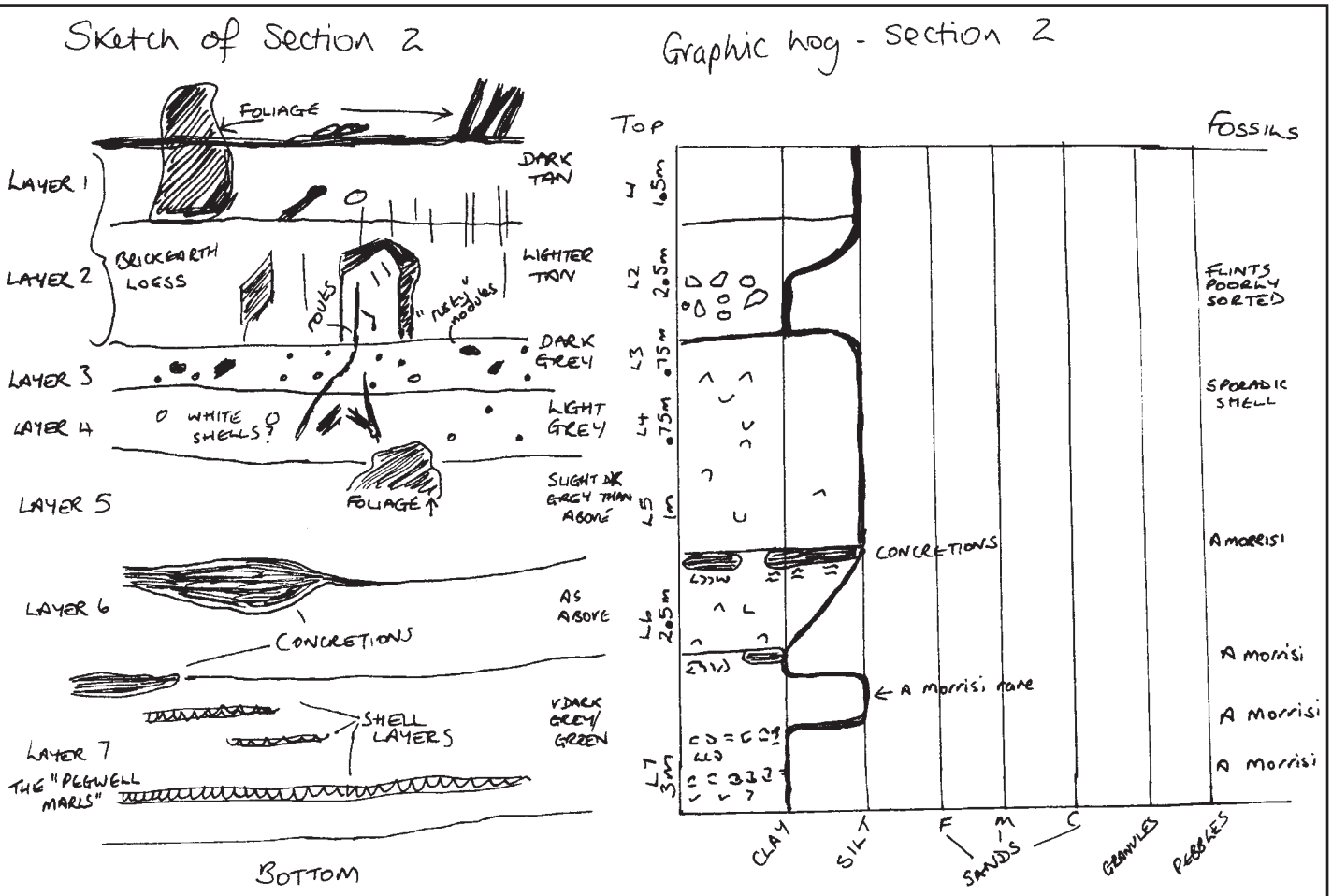


Figure 4. Graphic log & sketch of exposed geology. Layers 1 & 2 are the Brickearth, Layers 3, 4, 5 & 6 are the Reculver Silts, Layer 7 is the Pegwell Marl

Further to the south-west the basement limestones are overlain by Westphalian coal measures, which were deposited before the Cretaceous sediments in this area. However, the coal measures finish around Ebbsfleet (TR338620) and do not quite reach the bay.

Correlating the exposed geology to the geological history

Figures 3, 5 and 6 illustrate the unconformity between the Cretaceous Chalk and the overlying Thanet Beds. The chalk extends across much of the coast of south-east England. It has been shown to have formed under normal marine conditions as a white calcareous mud at a depth of between 100-600m (Toghill 2000, p145). Modern chalk sequences found in the warm shallow seas off the Bahamas have a negligible proportion of coccolith material (Gallois 1992, p39), leading one to question whether this contemporary environment is indicative of the conditions under which the Cretaceous chalk was deposited.

The Upper Chalk exhibits both nodules and extensive tabular sheets of flint (SiO_2) whose origin is controversial. The British Geological Survey (Gallois 1992, p40) suggests it could have come from either the post-depositional solution of siliceous skeletal remains, or by direct inorganic precipitation of silica from seawater. The Open University favour the former idea, suggesting that it accumulated randomly on the seafloor and was then dissolved under acidic conditions in the burrows of marine organisms (The Open University SXR260 2001, p109).

The presence of the Chalk shows that Pegwell Bay was a marine area during Cretaceous times. The environment must have been warm enough to encourage prolific production of coccoliths whilst, periodically, it shifted in favour of species secreting siliceous skeletons. Today, diatom[7] oozes predominate at high latitudes and radiolarian[8] oozes occur in tropical regions. However, silica oozes can also occur at the sites of coastal upwelling[9], whilst mixed radiolarian and foraminiferal oozes can occur where there has been a depression of the carbonate compensation depth[10] (The Open University, S330 - Ocean Chemistry and Deep-Sea Sediments, 2001, p72)

During the Cretaceous the Pegwell Bay area lay at about 45°N, hardly the warmest of latitudes. However, a greenhouse climate was prevailing and the Earth was a lot hotter than today. There was little temperature difference between equatorial and polar latitudes and an absence of ice at sea level (Woodcock & Strachan 2000, p339). Thus the exposed rock of the Upper Chalk is consistent with Pegwell Bay being located under a warm sea during the Cretaceous. One may continue to question the depth of that sea, and the environmental changes that facilitated switches from cal-

[7]Diatom - unicellular algae which secrete silica shells

[8]Radiolarian - zooplankton which secrete silica skeletons

[9]Coastal upwelling - a process whereby cool, nutrient rich waters are brought to the surface, replacing nutrient-depleted waters and supporting high rates of primary production

[10]CCD - This is the depth at which less than 20% of the carbonate skeletal material falling from the surface waters is preserved in the bottom sediments; the rest is dissolved during descent.

Figure 5. Thanet Beds near the sub-Eocene unconformity, note the wavy beds

careous to siliceous sedimentation.

The whole of southern England was gently uplifted during the early Tertiary period (65Ma to about 1.4Ma) as a result of ripples from compression in the Alps (Woodcock & Strachan 2000, p384). This exposed the Upper Chalk to sub-aerial erosion which removed the earliest Tertiary sediments.

Figure 6. The Thanet Beds. Above: Close-up view of wavy bedding in Thanet Beds near the sub-Eocene unconformity. Below: Closer to Ebbsfleet the Thanet Beds exhibit linear stratification.

A shallow sea then transgressed across the area, extending into the London Basin (Woodcock & Strachan 2000, p384). Pegwell Bay was a near-shore area in which the sandy facies of the Thanet Beds were laid down. The sub-Eocene unconformity (Figure 3 shows the type section) marks this marine transgression and the start of deposition of the Thanet Beds (from about 65Ma). The major feature is the Bullhead Bed: a layer of unworn, glauconite coated flints in a matrix of dark clay and glauconitic sand. Maizels (1975, p12) suggests that it may "represent the first 'beach' of the rapidly extending Thanet Sea" and dates the unconformity at around 100Ma, with deposition of the overlying Thanet Beds from about 70Ma. English Nature describe the 'Bull-head Bed' as "an *in situ* weathering residue of unabraded flint nodules".

Maizels' suggestion is not conclusively supported by the field evidence. However, the angular slabs of flint do not exhibit the signs of mechanical abrasion that would be expected in the littoral zone (arising from the action of tidal currents and waves) or supratidal zone (arising from sub-aerial erosion). There is also some evidence of small-scale cross-stratification in the sands above the unconformity, possibly indicative of wave-formed ripples, and the sandy nature of the deposits is suggestive of a continental shelf environment. It is likely, therefore, that this bed was laid down in a medium energy, off-shore environment, at a depth of up to 200m[11].

Figure 4 shows a sketch of one section at Pegwell Bay and its associated graphic log. The graphic log was constructed by taking samples from a number of positions along the cliff exposure behind the old hoverport apron.

The Thanet Beds themselves are composed of fine, glauconitic sands and fossiliferous sandy clays. There is a 16 inch shell bed at the base of the Reculver Silts[12] which contains an important fish fauna. This is preserved as disarticulated fish debris including a diversity of identifiable shark teeth. This is the only outcrop

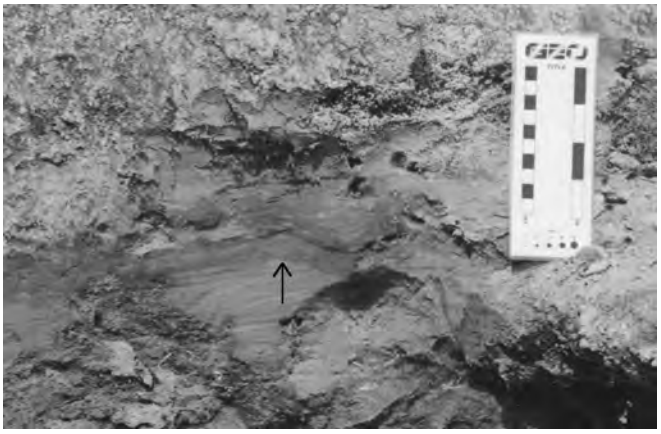
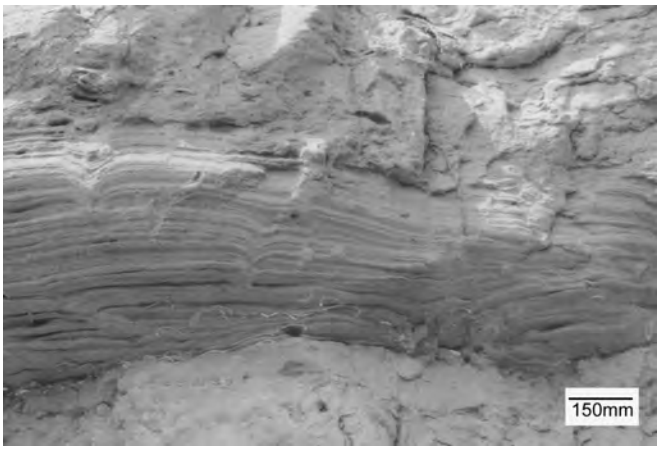


Figure 7. Small scale layering in the Reculver Silts. Note the pale grey lenses of silt and that sediment appears to have flowed over them (arrowed).

[11]Storm waves can affect sediment as deep as 200m; below that, waves have little effect on bedforms.

[12]See English Nature, SSSI Notification for Sandwich Bay and Hacklinge Marshes, File reference TR/35-4



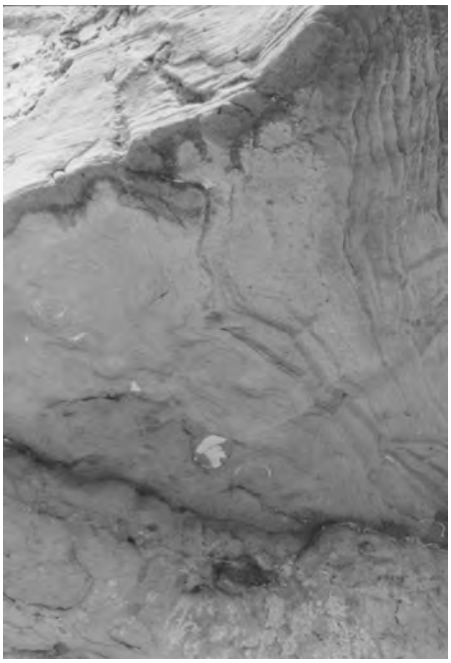


Figure 8 : Sandstone doggers bounding Layer 6 of the Reculver Silts. Top:lower boundary of Layer 6, note shale-like, fissile nature of the concretion; middle: upper boundary of Layer 6, note presence of white (probable) *Arctica morrisi* shells at the lower surface; bottom: lower edge of concretion at upper boundary of Layer 6, note presence of ripple-like features and (probable) *A. morrisi* shells. Width of photograph ~1m.

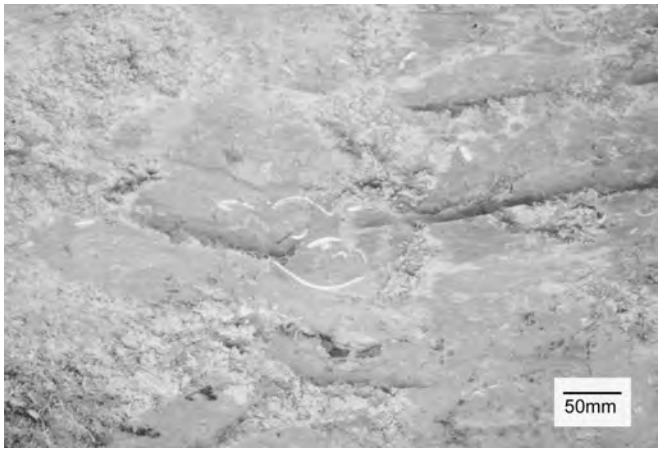


Figure 9. (Probable) *Arctica morrisi* fossils in the Reculver Silts, not in life-position.

which shows the bottom-living fish assemblage which was subsequently destroyed by the North Sea volcanicity. Ash falls brought about an extinction event at this time.

At the site illustrated in Figure 3, the overlying Thanet Beds are about 4m thick and a light grey-tan colour. Just above the sub-Eocene unconformity there is a darker and more clay-rich horizon. At this location the Thanet Beds appear to be a massive deposit with little layering (excepting the cross-stratification noted earlier). However, as one moves along the section towards Ebbsfleet, there is evidence of some wavy-bedforms and large-scale cross-stratification (Figure 5), before the sequence settles into parallel bedding (Figure 6). Small-scale layering is visible within the Reculver Silts (Figure 7).

Layer 6 is bounded to the top and bottom by irregularly spaced sandstone concretions (Figure 8). Golding (2003) notes that various authors have commented on these "doggers" and suggested that they may have been formed by storm events acting on impersistent beds of clean fine sand.

The overall impression of the Reculver Silts is of a low-energy marine environment which was mostly below the storm-wave-base. Sands and silts were deposited with some layering which in places appears to have suffered little bioturbation. Occasionally storm-waves disturbed the sea-floor and produced the doggers; perhaps the water depth was shallow or the storms particularly vigorous at those times. The *Arctica morrisi* shells found throughout the section (see Figures 8 and 9) are typically broken or not in life-position; these may have drifted in from elsewhere.

The capping flinty layer suggests that this area had become a higher energy environment, perhaps representing the emergent Thanet 'beach' (Figure 10) . Close examination of this layer, a little closer to Ebbsfleet, shows it to be composed of a mixture of well-rounded to sub-rounded, small calcareous clasts (they react with HCl). These clasts can be scratched with a knife and, whilst being quite hard, are white in colour and probably a hard chalk. Mixed in with these small clasts are larger fragments of flint, ranging in size from small to very large pebbles. These flint pebbles range in shape from sub-rounded to angular and exhibit varying degrees of wear, although many appear not to have been transported far. The presence of these relatively fresh flint clasts is suggestive of active erosion of the Chalk close to where this sediment was being deposited. Both the flints and calcareous clasts are held

Figure 10. Capping flinty layer at top of Thanet Beds (boundary with Brickearth).

in a very fine sand matrix.

Above the flinty layer the Thanet Beds are covered by ~2.5m of Brickearth (based upon field observations near the site of the sub-Eocene unconformity). This is a tan-coloured loam, showing little structure, which may have been deposited sub-aerially during the last glaciation. This Head[13] deposit is the "Younger Brickearth" and is described by Gallois as a "buff, structureless loam or silt". Some brickearths "resemble the loess[14] deposits of northern Europe and may be wind-borne, others probably accumulated in shallow water during a period of dry climatic conditions" (Gallois 1992, p62). Where the deposits contain angular stones and pockets of flint gravel they may be the result of redistribution of earlier deposits by solifluxion[15] or by widespread 'sheet-flooding'. English Nature assert that there is up to 4m of Devensian (15-18 Ka) loess overlying the Thanet Beds, produced "under periglacial conditions during the [last] Ice Age". Apparently "where the loess rests on the chalk, there is often a highly frost-shattered zone with well developed involutions. Pegwell Bay provides the best exposures of true loess deposits in Britain; they are exceptional in having escaped modification by

Figure 11. Shell deposit in the Younger Brickearth, not in life position.

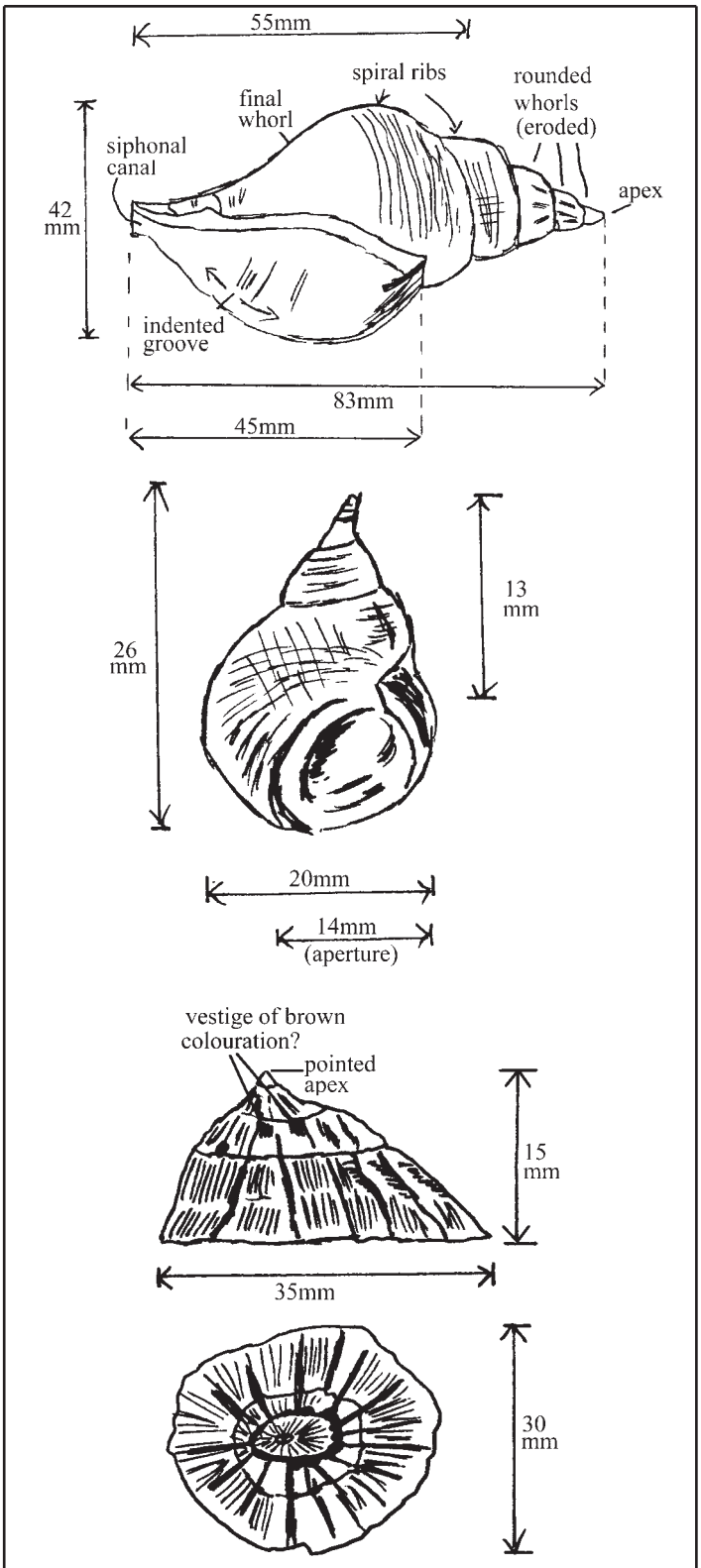


Figure 12. Fossils found in the Younger Brickearth. Top: *"Siphonalia" subnodosa*. Middle: unidentified winkle. Bottom: unidentified limpet.

[13]Head deposits are formed by water lubricating the movement of grains, rather than transporting them as bedload or in suspension (Gallois, p59,62).

[14]Loess: silty deposit; thought to be wind-blown from areas glaciated in the Pleistocene.

[15]Solifluxion - a process whereby water lubricates the movement of material rather than being the agent of transport (Lapidus & Winstanley 1990.)

solifluction"[15].

The Younger Brickearth has been found to contain fossil gastropod (*"Siphonalia" subnodosa* plus unidentified winkles and limpets) and bivalve (unidentified species similar to the Common Blue Mussel, *Mytilus edulis*) shells (see Figures 11 and 12); as well as a fragment of bone from an unidentified (possibly) mammalian animal (sample examined by S Wells, Natural History Museum, NHM reference 03-0008).

Summary

It is clear that for a significant part of its history Pegwell Bay has been submerged beneath sea water. The depth of that water has varied over time from a shelf-sea environment (100-600m) to a sandy near-shore environment. Two periods of time when the Bay has been land are revealed firstly by the absence of Triassic and Jurassic rocks, and secondly by the Sub-Eocene unconformity.

Changes in the physical environment and paeleolatitude have resulted in different sedimentary facies being deposited. Over time limestones, sands, clays and biogenic chalk have registered the passing of various marine environments. The presence of the Younger Brickearth records the passing of periglacial conditions and the emergence of the Bay as land.

Study of Pegwell Bay to date has only scratched at the surface of its geological history. Further work will reveal a more detailed account of the depositional history of the Chalk, the Reculver Silts and the Younger Brickearth.

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Author

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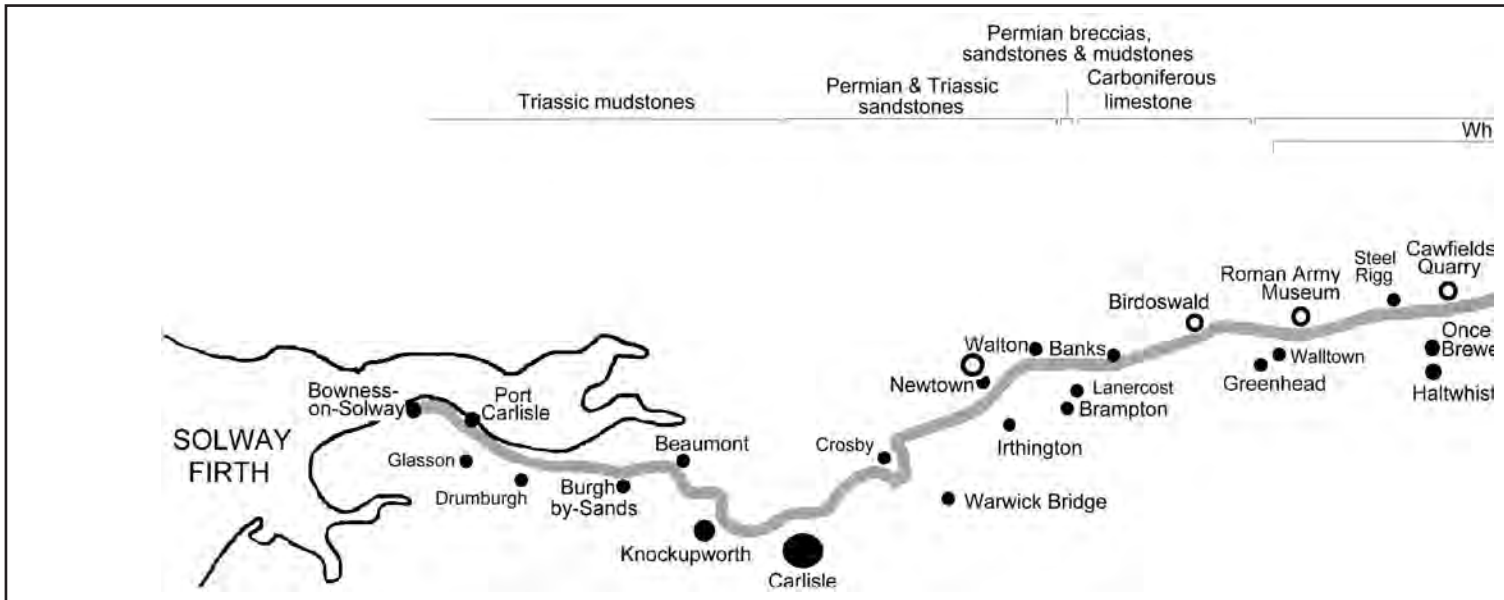


Figure 1. Hadrian's Wall

Geological obstacles to the construction of Hadrian's Wall

G A L Johnson

Hadrian's Wall was the northern frontier of the Roman Empire. It crosses Britain by the shortest route from near the mouth of the River Tyne in the east to the Solway Firth in the west (Figure 1). It was planned by the Emperor Hadrian and was to be constructed of sandstone, 3m wide and up to 4.6m high with a crenellated parapet probably of 1.8m. A massive wall of this type is unusual on a Roman frontier line. Other frontiers are marked by narrow stone walls, dry stone walls, wooden fences and barriers formed of turf. The northern frontier in Britain is quite different and was conceived to protect, with its forts, the line of communications east to west along the River Tyne valley from raids by the northern barbarian tribes.

Building the wall started in AD122, but progress was slow because of the vast volume of sandstone needed to produce a wall of these dimensions. There was no shortage of sources of sandstone and small quarries were opened along the line of the wall in the eastern sector. Not only the masoned external blocks were of stone, but also the core of the wall was filled with broken stone and bonded with clay or mortar (Figure 2). By AD124 it was decided

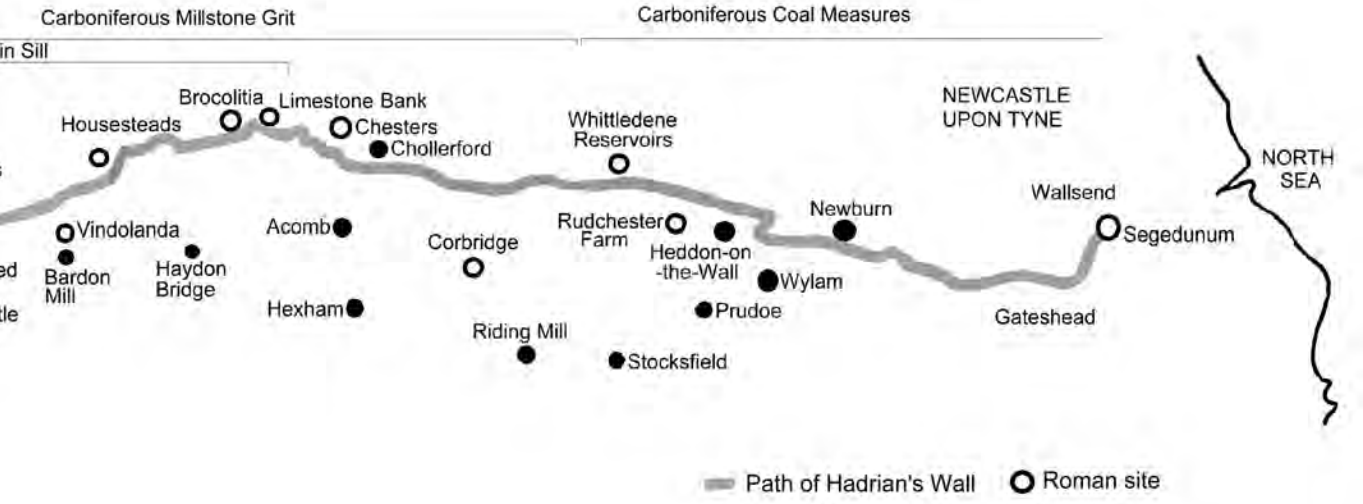
Figure 2. Cross section of wall showing rubble infill at Walldown Quarry. © Alan Hamilton.

Figure 3. Housesteads Fort. © Alan Hamilton.

to reduce the width of the wall to 2.3m to save materials and speed construction; intermediate dimensions were also used. At the same time it was realised that the forts along the Tyne Valley were too far south of the wall and sixteen new wall forts on the line of the wall were constructed at intervals of five Roman miles. The forts provided barracks for the garrison that manned the wall and were also gateways and trading posts through the wall. (Figure 3).

In addition to the sixteen major forts, milecastles were built into the wall at intervals of one Roman mile, each of which housed about thirty soldiers. Two turrets were constructed between the milecastles, each one third of a mile apart, which sheltered nine men each (Figure 4).

Earthworks associated with the wall consisted of a ditch in front of the wall (on the northern side) which was 9.2m wide and 3m deep, which was excavated except where the wall was on top of a high cliff. Behind the wall on the southern side there was a



and the rocks over which it passes.

Figure 4. Cawfields milecastle. © Alan Hamilton.

marching road or military way, which had a cambered surface and was metalled with broken stone. Further to the south of the road another ditch 6m wide and 3m deep with mounds either side, called The Vallum, formed the southern boundary of the Roman frontier zone (Figures 5 & 6).

The wall seems to have been mainly completed from the Tyne to Solway by AD130 and alterations to forts, gateways and ditches continued to AD160. The frontier was moved North to a line between the estuaries of the Forth and the Clyde in Scotland by the Emperor Antoninus but following trouble in the North of

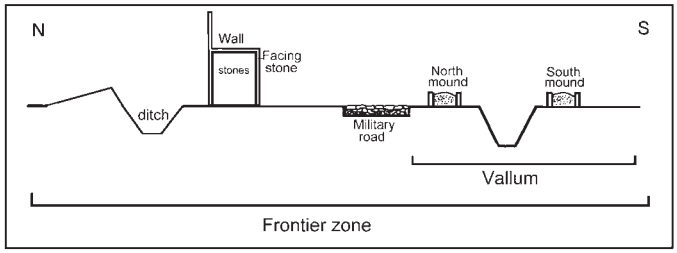


Figure 5. Sketch of cross section of frontier zone.

Figure 6. Aerial view of Hadrian's Wall running along the top of the crags on the left and the Vallum running in the valley below to the right. Published with kind permission of English Heritage.

England the Romans fell back to Hadrian's Wall which had to be repaired by Severus about AD200. The wall was garrisoned until about AD400, but by then Roman administration had come to an end and there was no longer the need for a marked frontier. The wall ceased to be manned altogether by about AD410.

The broad history of Hadrian's Wall described in the previous paragraphs is a story of achievement. Surveyors planning the route for the wall, found the shortest way and utilised the almost east-west line of Whin Sill cliffs that form a natural barrier. They found the best line for the wall to take it across Britain. There were no difficulties in constructing the frontier zone in the east where almost continuous boulder clay allows excavation of ditches and sandstone for building is readily available. This situation persists westwards to the River North Tyne. Here the central sector of the frontier begins with more upland country containing

Figure 7. The Whin Sill outcrop at Walltown Quarry. © Alan Hamilton.

many crags and ridges of bedrock with thinner and impersistent cover of boulder clay. Bedrock consisted of Carboniferous sediments including thick sandstones, so adequate building materials were available. Initially few difficulties were encountered and the frontier zone was extended westwards in the same pattern as before. However at the top of Limestone Bank, above Chollerford, they encountered an igneous rock for the first time. This was the quartz-dolerite of the Great Whin Sill (Figure 7). It is dark grey or black, very hard massive rock cut by only small joints. It is a very difficult rock to excavate and quite different from the Carboniferous sediments used previously. However the Roman engineers made no special preparations for the hardness of the Whin Sill and continued to push forward the ditch and the Vallum in their standard positions. They were not entirely successful. They produced a ditch before the wall and a Vallum, but the large blocks produced by splitting along joints in the Whin were too massive to move out of the trench by hand and too massive to be split further. One of these large blocks still lies at the bottom of the ditch today with wedge holes cut along small joints in an attempt to split the rock clearly visible.

Figure 8. Hadrian's Wall running along the top of the cliffs at Housesteads looking east. © Bob Alderman.

Although partly defeated by the quartz-dolerite of the Whin Sill, the building teams had managed to get the frontier zone on to the south side of the Whin Sill outcrop. In doing this they successfully incorporated the Whin Sill scarp and cliffs, a little way further to the west, as part of the frontier zone (Figure 8). Care was clearly taken that the path chosen for the frontier would require no further excavation in the quartz-dolerite sill. Where it was next encountered near Sewingshields, the wall continues westwards and rises on to bold Whin crags while the Vallum trends southwest to miss the quartz-dolerite outcrop and stay on Carboniferous sediments for easy excavation. There was another factor that the wall builders and ditch excavators had to contend with starting to the west of Limestone Bank: extensive basins filled with wet peat formed another obstacle to both finding a foundation for the wall and to producing the ditch and the Vallum. The surveyors for the line of the frontier zone had to find a path missing both the dolerite sill and the deep peat basins. The limiting dimensions laid down by Hadrian for the frontier zone had to be abandoned and a more flexible pattern adopted dependent on the local ground conditions. This particularly affected the distance between the Vallum and the wall which is variable owing to ground conditions between Sewingshields and Walltown.

Throughout the upland central sector of the frontier zone the wall was built on the top of the north-facing escarpment of the Whin Sill, often above high vertical cliffs where no ditch before the wall was required. The Whin dolerite ridge and cliffs were now incorporated within the frontier zone. This was satisfactory so long as the scarp and the cliffs maintained their east-west direction. But at the end of the line of cliffs at Walltown above Greenhead the Whin outcrop turns to the southwest in faulted and drift-covered ground. To continue its east-west course the frontier zone had to cross the Whin Sill outcrop and a low point in the Whin scarp was chosen for this at Walltown where only a limited amount of excavation in the quartz-dolerite was needed. Unfortunately the exact paths of the original wall and ditches here are lost owing to later quarrying.

Continuing past Greenhead the frontier zone is built over deep glacial drift where a more regular pattern of wall and ditches could be maintained. These conditions persist westwards to near Lanercost, with the frontier taking a strong position on high ground above the River Irthing. Still on Lower Carboniferous bedrock with thick sandstone bands, building stone was available near to the line of the wall and quarries were developed along the River Irthing.

In the vicinity of Lanercost the Carboniferous bedrock is replaced by Permo-Trias New Red Sandstone which onlaps eastwards at the eastern margin of the Carlisle Basin. Early workers called this structure the Red Rock Fault, but hereabouts it is an unconformity largely masked by glacial deposits. There are no exposures of bedrock on the line of the frontier zone for 30km west of Lanercost to the end of the wall at Bowness-on-Solway. Those that planned the wall may well have anticipated this lack of building stone because, in the first phase of building, they decided to make a barrier of turf rather than a stone wall from the River Irthing west to the end of the wall. The turf wall was progressively replaced later by stone so that by the beginning of the Third Century there was a stone curtain wall stretching from the Tyne to the Solway.

The lack of local stone west of Lanercost was another obstacle delaying the completion of the stone wall. Stone was carried 5km north to the frontier zone from quarries in New Red Sandstone in the gorge of the River Gelt, a tributary of the River Irthing, where there are carved inscriptions left by the Roman quarrymen.

There was no difficulty in excavating the ditch before the wall and the Vallum in the deeply drift-covered ground west of Lanercost and to the River Eden at Carlisle. The frontier zone takes the crest of a low boulder clay ridge on the north side of the Irthing valley for 12.5km to Carlisle. This gave better-drained conditions for both the foundations of the stone curtain wall and the ditch and Vallum. West of Carlisle, the frontier zone follows higher boulder clay covered ground on the south bank of the River Eden to the village of Beaumont and then turns west towards the Solway coast at Burgh-by-Sands. The irregular surface of the boulder clay caused the wall to change direction fairly frequently, thus adopting a zig-zag plan while the Vallum cuts out the zig-zags by running in straight lines between the major southerly bends in the wall. This setting of wall and Vallum running independently in zig-zag pattern is a feature of the west end of the frontier zone and is seen again to the east of Bowness-on-Solway. At Burgh-by-Sands the frontier zone descends from the higher ground of boulder clay on to the marshy shore of the Solway Firth. No trace of the wall and ditches can now be seen on the salt marsh and the foundations must be deeply buried in the marsh. How the builders obtained a foundation in this soft ground is uncertain and even the exact course of the frontier across the marsh is unsure.

On the west side of the East Marsh the frontier zone can be found climbing to higher ground, formed by an eroded drumlin composed of boulder clay at Drumburgh. Other low boulder clay 'drumlinoid' hillocks occur along the south Solway coast at Glasson, Port Carlisle and Bowness-on-Solway separated by stretches of flat marine terraces and salt marsh near to sea-level. The frontier zone picks its way westwards along the coast from one hillock to the next always seeking better-drained conditions for the foundations of the wall and ditches. A run of zig-zag wall was produced that ended at Bowness, the most westerly wall fort of Maia and the end of the wall. The frontier zone continues south down the Cumbrian coast in a series of fortlets and towers constructed of turf and timber, but Hadrian's Wall itself ends at Maia, Bowness-on-Solway.

The basic plan for Hadrian's frontier zone of a stone curtain wall with ditches was maintained from east to west across the isthmus of Northern England. Starting in the eastern sector the basic plan was followed directly because the local ground conditions combined continuous drift cover with abundant building stone and so allowed this. At the beginning of the central sector, more rugged upland conditions with extensive bedrock outcrops and deep basins of wet peat produced special ground conditions that made alteration and deviation of the frontier zone inevitable. The hard and massive quartz-dolerite of the Whin Sill was also encountered at Limestone Bank and a decision may well have been taken not to excavate ditches through it again. The Vallum carefully avoids the sill on its course westwards.

In the western sector and particularly to the west of Carlisle, the course of the frontier zone follows the most favourable route across the ground conditions present. This leads to local changes in the frontier zone, such as the zig-zag wall of Bowness. The Roman surveyors and builders seem to have become skilled at adapting the form of the frontier zone to fit with the prevailing local ground conditions, but they never wholly abandoned Hadrian's basic plan. With exceptions, the stone curtain wall and Vallum ditch are continuous westwards from the River Tyne to the end of the Roman northern frontier in Britain at Bowness-on-Solway.

(Further reading by the same author "Geology of Hadrian's Wall", Geologists' Association Guide No 59. 1997. 89pp)

Acknowledgements

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Book review

Exploring Space, Exploring Earth by Paul D Lowman Jr, 2002, Cambridge University Press, 362pp, £29.95 paperback, £80.00 hardback, ISBN 0521890624 (Pb) 0521661250 (Hb)

This is not a book for the feint of heart nor a book to leave on the coffee table to be dipped into for a leisure activity, rather it is a well researched, well illustrated and a well referenced book. The basis of the book discusses the results obtained by using systems and equipment designed to explore space to explore the surface of our own planet.

Geo-stationary satellites, Global Positioning Systems, RADAR alitimetry, data from Landsat and Magsat are all employed to provide new and exciting information. Satellite Laser Ranging (SLR), Very Long Base Interferometry and Satellite remote sensing data also provide fascinating insights into how the earth 'works'.

From the outset the author assumes that the reader has more than a passing knowledge of earth sciences and geology in particular, and without that knowledge much of the content would not make a great deal of sense.

Having said that the seven chapters are distinct but overlapping, one flowing neatly into the next. The subjects covered range from plate tectonics through geomagnetism, impact cratering and even touches on how life from its humble beginnings has impacted on the earth.

There are comparisons between gravitational systems on the earth and other planetary systems, atmospheres (or lack of), the evolution of the inner planets and even the possibility of extra terrestrial life. It also attempts to give us a greater understanding of the processes involved in environmental geology with excursions into such areas as desertification, glaciation and deforestation.

The author acknowledges in the afterword that the book "reflects his own concepts of terrestrial geology", but never-the-less I believe that the book is guaranteed to start the serious geologist looking at traditional ideas and concepts in a slightly different light.

Chris J Applebee BSc (Hons). MSc.

The meaning of Rock and the Dark Arts

Graham Scarr

Have you ever wondered about the point of having all those big lumps of rock lying around all over the place that make up continents, mountains and the like, with fluffy bunnies skipping over extinct volcanoes and limestone pavements? Pretty they may be and good for the holiday snaps, otherwise where would we be without a nice bit of scenery, but what about all those fancy paintings with sheep grazing on top of glacial till, or whatever is underneath - good for the soul? Ah, "the seaside" I hear you say. Lots of little bits of rock battered down to size to create the perfect sandy beach, with a backdrop of towering cliffs revealing strata of sedimentation, and dinosaur bones poking out enticingly just waiting to be collected by anyone passing. Well, let us try buildings, majestic cathedrals made of blocks of precision hand-carved limestone and sandstone, with arches that get stronger the more you pile on top of them. The simple stone croft, lovingly constructed from what was to hand with no pretensions except it was somewhere to live. Nowadays brick has become an art form, and deservedly so, but it is made of rock which was once pounded into clay. "Concrete and roads"! Well, that is all very well, but unless it can be seen for what it is, it might just as well be papier mache in there for all I know. No, the answer, dear reader, is to be found ... wait for it ... at the stonemasons...

Approaching the storage yard I observed a metal fence, obviously designed to contain rather than keep out, but what did this mean? Noting the 2.5m x 1.8m x 15cm-ish slabs of stone, polished on one side and stacked horizontally on wooden battens in such a way so as to contain the more restless ones at the bottom, I proceeded cautiously. A multitude of other shapes and sizes soon emerged with the same sorts of stone together, presumably for companionship, but the wilder ones were contained in wooden crates and there was the odd one or two whose contents had got away... Altogether there were dolerites and granites from India and China; granites from Sweden, Norway, Finland and France; bioclastic and oolitic limestones from Italy; gabbro from the Bushvelt in South Africa; Ordovician slates from Cumbria; sandstones from Yorkshire, Italy and China; Larvikite from Norway and the famous grey and white marbles from Carrara. I was in paradise and there before my very eyes I saw the result of what this was all about. They might be gravestones to some people, but they really were a superb display of what stone looks like when treated properly. Yes, stone was destined to be POLISHED.

Stonemasons, unlike geologists, have got rock classification well sorted because there are only four types!

1) Stone - this is essentially limestone or sandstone, which usually does not take a polish well, and consequently generally has a coarse finish.

2) Slate - grey, black or green matt finish.

3) Marble - now this can take a polish but it is wasted if left outside as acid rain attacks the surface, in which case it is best left rough. However, the grey and black ‘marbles’ from Derbyshire, although still strictly limestones, can take a good polish.

4) Granite - or in other words - everything else - has pretty names like Balmoral Red, Tropical Green, Bahama Blue and Star Galaxy (see Plate 1 centre pages).

I had to find out more about all this so, heading towards the workshop, found many vertically and neatly stacked pieces of partly worked stone shapes, all completely different and with no apparent order, presumably sharing the genetic pool and another row of headstones waiting to have new names added. Okay, so stones do not have genes, but it did look rather suspicious, all that intermingling. Memorials tend to be fairly plain, evenly grained rock, whereas office fronts and kitchen worktops are more veiny and patterned, but I did spot some rather splendid Paradiso Pink from India, which is a granite with a flow structure that would have needed a rather trendy vicar to allow in the churchyard. Inside were several skips full of what the workers affectionately call “off cuts”. I managed to rescue a few of these for the garden and they will look very nice against the azaleas next year. As to the noisy stuff, saws tipped with diamond come with their own playstation gamepad and lots of buttons and lights to set the depth of cut and speed, and slice through 8cm of granite as if it were butter. The laser is used for measuring, (or so the man told me, but I have seen what they really do with these things on Startrek). The profiling and milling machines cut the fancy bits as well as edge mouldings and decorative effects. Polishing machines with finer diamond grit finish off the reverse face and edges, which is an automatic process (I do worry about intelligent machines). These machines use a lot of water for lubrication and cooling, all of which is recycled through a treatment plant and reused, the slurry sent off to be mixed with epoxy resin to make garden ornaments. Maybe it really is all for the benefit of the fluffy bunnies - but I digress. Inside the Masons’ Shop the chaps were carving figures onto the surface of white marble using angle grinders and pneumatic chisels. It takes several days for the more elaborate ones but they would not let me have a go, maybe because I had already spent two and a half hours poking about. It seems that other people do not take quite so long, probably being more focussed on the pub at the end - how perverse!

Time is running short and we have got to get on, but let me just complete this bit by telling you about ‘letting’ (lettering to you and me). A computer-controlled cutter makes a stencil out of rubber sheet which is stuck on the stone, sandblasted to a depth of 1mm and the letters painted with enamel or gilded with 23.5 carat gold leaf, OR, filled in with lead and planed smooth, OR, chopped out with a hammer and chisel. I am not sure about the ethics of doing this to such nicely polished stone but I suppose that this is what really pays the bills. One of the most interesting and complicated requests is the addition of a design such as a military crest. A picture is scanned onto photosensitive paper, stuck on the stone and sprayed with pressurised water. It is then washed away leaving a stencil which is sandblasted as above.

It does, however, seem a little sad that such beautifully crafted stone will eventually end up being forgotten about in the corner of a cemetery somewhere (fluffy bunnies again), although that does provide a venue for generations of geologists to see stone which they might not otherwise encounter.

Which brings me nicely to those other lumps of rock which are shouting out “look at me” whenever they can. Sadly most people’s appreciation of jewellery is “how much is it worth?” and

"does it match the shoes and handbag?" Gemstones (they are not called rock anymore so as to disguise what is happening to them) come from under the ground and all those goings on down there over millions of years, with enormous temperatures and pressures wreaking havoc by melting, twisting, folding, crushing (I could go on), do so until conditions are such that the lumps that we are really interested in can form. It is just chemistry, love at first sight between different elements who, given the right conditions, just cannot resist each other and crystallize in whatever space is avaiable. So, you will not find a topaz if there was not any fluorine around, or a sapphire if there was a lot of spare silica as the aluminium would have grabbed it and formed something different. Fortunately, nature has evolved the geologist who can look at the surface and divine what might lie under it, dig a hole and find those lumps of precious something - that is why they are called jollygists, because the clever chaps seem to have a knack of getting other people to actually dig the hole.

Opaque stones can be cut and polished with diamond saws and grits into circular or oval domes called cabochons, which brings out the best in a pattern, such as malachite, onyx, agate etc. but the real ultimate is the facetted stone, usually transparent, which makes best use of the optical properties of refraction, reflection, dispersion and colour (see Plate 1 centre pages). The best known example is the diamond which has many flat surfaces all at a specific angle designed to enhance the appearance, the cut most commonly used and giving the best light return being called the 'standard round brilliant'. In my opinion, any diamond with a diameter less than 10mm is best stuck on the end of a drill bit and put to good use making a hole for itself (which is their other function). Diamonds are not as rare as we are made to believe. This is because the places where they are found are mostly controlled by men in suits and machine guns who regulate their supply, stick lots of little ones on nearly every piece of jewellery, spoil a nice coloured stone, and bump up the price. Synthetic diamond simulants like moissonite (silicon carbide) and cubic zirconia (zirconium oxide) look exactly the same to most people, are far cheaper to buy and, even if I could tell the difference I would still appreciate them for what they are, but enough of the soapbox.

Coloured stones have been facetted for hundreds of years by trial and error to get the best shapes, and still are in some places, but now simple computer programs can design a cut, show what the optical effects will look like and print out all the angles so that the best can be achieved for any particular piece of rough stone. The angles are made so that light entering the stone is internally reflected, leaving the crown and making it sparkle. They are dependant on the refractive index so that just a couple of degrees out can make all the difference between a sparkler and a very dull stone. This is why so many coloured stones can appear lifeless because to use an angle which would have made them sparkle would have resulted in a very deep pavilion (the underside) and cumbersome setting, but it would have been worth it.

The principle of cutting is to hold the stone in position against an abrasive surface, cutting all the facets in turn and working through finer grits until polished. The abrasive is diamond or silicon carbide powder on a metal plate called the lap. Simple. But that is where it becomes complicated, because to hold the stone in EXACTLY the right position and return to it as necessary requires a fancy and expensive bit of kit. They are very precise and accurate but beyond the reach of the novice, which is why I built my own for a few pounds out of old wood, bits from car boots and lots of araldite and, just so you know what is possible, cut a stone which did alright in a facetting competition. To do the same yourself you can start with some bits out of that old printer and video recorder that broke down last year, you did save them didn't you? ... oh dear, well perhaps another time then.

Gemstones have been the pursuit of kings and peasants alike, memorials the markers of great events and people; it is because they are polished that they take on a life of their own and grab our attention. The process of cutting and polishing rock in all its forms is absorbing to the verge of an obsession, but what better geology than finding the rough on a field trip having worked out where it was likely to be found in the first place, and cutting and polishing it yourself.

Acknowledgments

Thanks go the Anthony Lidster who showed us round his workshops and provided the photographs and descriptions of the granites. Gemstone images courtesy customgemstones.com ©2004.

Author

Graham Scarr works as an osteopath but has an interest in anything geological. He used to work as a research laboratory technician in microbiology and is a keen supporter of 'do it yourself' technology.

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Book review

Snowball Earth by Gabrielle Walker, 2003, Bloomsbury, 269pp (hardback) £16.99, ISBN 074756051X.

Brian Harland originally proposed the theory in 1963; Joe Kirschvink looked at it again, became very excited but only wrote a two page monograph naming it about it in the late 1980s; so it was left to Paul Hoffman and Dan Schrag to draw the theory of Snowball Earth together in the 1990s. Their theory ran that towards the end of the pre-Cambrian, the Earth froze completely, from pole to equator. Not once, but up to five times (Walker doesn't seem certain if it's four or five times, depending on which chapter you're reading). Volcanoes belched out enough carbon dioxide to warm the planet up and melt the ice, and this process ultimately led to the Cambrian explosion.

Of course there were many challenges to the theory and the book details attempts to discredit the scheme and the way that Hoffman and Schrag rebuffed or absorbed their critics' attacks into the plan. It's very readable, very definitely a 'popular science' tome, so not a lot of complex terminology, though a bibliography that lists the various scientific papers for those who want to check them out. It may be around 250 pages, but it's big print, so shouldn't take too long to read (I managed it one Sunday recently recovering from a hangover the size of Leicestershire). There's quite a lot of extraneous biographical detail about many of the main players, as well as GW's experiences with stromatolites at Shark Bay and face to face with an angry elephant in Namibia, but these silly bits aside, it skips along nicely and it's hard to put down. Worth a borrow from your library, but if you want to buy it, I'd suggest hanging on for the paperback version.

Fred Tomsett Continuing ES student

Relationship between worldwide underground nuclear tests and worldwide major earthquakes with magnitude 7.0 or greater

Michael R Franke

Abstract

This paper investigates the possible relationship between worldwide underground nuclear testing and worldwide major earthquakes with magnitude 7.0 or greater, and by inference whether seismic waves, generated by underground nuclear testing, trigger earthquakes. To analyse if there is a relationship, the seismic record is divided into three time periods: the pre-nuclear test period, the nuclear test period and the post-nuclear test period. These data and data of underground nuclear testing are used to plot a graph. This graph show no increase of seismic activity in the time range of underground nuclear testing. Thus, the data indicate that there is no positive correlation between seismic waves, generated by underground nuclear testing, and major earthquakes with magnitude 7.0 or greater but there is a possibility of negative correlation during the testing period.

Introduction

The central points in this paper are not the essential problems of nuclear testing for the environment e.g. radiation and other harmful effects. In this paper the core question is, whether there is any relationship between underground nuclear tests and worldwide major earthquakes with magnitude 7.0 or greater, or can seismic waves generated by underground nuclear tests trigger an earthquake. The trigger for this investigation was recurrent discussion on this theme in the media and research papers. In 1989 G. T. Whiteford, Professor of Geography at the University of New Brunswick in Canada, described the relationship between nuclear testing and earthquakes with magnitude 5.8 or higher (Whitford (1989). Whiteford studied the total number all of earthquakes with magnitude 5.8 or higher starting from the year 1900. He compared the earthquakes rate before nuclear testing and for 1950 to 1988. From 1900 to 1950 earthquakes with magnitude 5.8 and higher occurred at an average rate of 68 per year, during the nuclear testing time 127 per year. Thus, the rate of earthquakes > M 5.8 is doubled during the time of nuclear testing.

In my investigation the nuclear test period runs from 1951 to 1996, because underground nuclear testing began in 1951 in the United States and ended in 1996 with two tests in China and one test on the Mururoa atoll.

Methods

In this investigation two sets of data are used: the number of earthquakes per year with a magnitude 7.0 or greater in the time 1900 to 1999 (USGS 2004) and the number of known nuclear tests worldwide in the time 1945 to 1996 (NRDC 2004) conducted by the following five nuclear testing nations: United States, Soviet Union, United Kingdom, France and China. The earthquake data are divided into three periods:

1.The pre-nuclear test period (1900 to 1950)

2.The underground nuclear test period (1951 to 1996)

3.The post-nuclear test period (1997 to 2003)

From the data of known nuclear tests only the underground nuclear tests, beginning 1951, are used. From the complete set of earthquake data and every period, the average annual rates of all earthquakes > M 7.0 in the time 1900 to 2003 are used to determine the proportional variations between the three periods. The data of the nuclear test period and the number of earthquakes in the period 1900 to 2003 are used to plot a graph to analyse the trend (Figure 1).

Results

In the years 1900 to 2003 a total of 2051 earthquakes occurred with magnitude of 7.0 or greater. The average rate is 20 earthquakes per year. In the period 1951 to 1996, 1482 underground nuclear test explosions occurred worldwide.

During the underground nuclear test period, 1951 to 1996, the earthquake rate per year is 9.5 % below the long-term (1900 – 2003) average rate of 20 earthquakes per year.

The most active year since 1900 was 1943 (pre-nuclear test period) and the least active year since 1900 was 1986 (nuclear test period). There is no correspondence with peaks of seismic activity and nuclear testing. In the time range 1967 and 1988 there is a downward trend in the seismic activity recognizable, but the rate of nuclear tests remained high, at of 50.4 per year. This total of 1058 nuclear tests represents 71% of all underground nuclear tests in the nuclear testing period 1967-1988. After 1988 the rate of underground nuclear tests decreases and the earthquake rate shows an upward trend.

Table 1. The variations of earthquakes > M 7.0 per year in the three periods and the variation in average of Earthquakes >M7.0 per year in percent. The number of earthquakes per year has decreased since 1900.

Period	Year	Number of Earthquakes >M7.0	Average Earthquakes >M7.0 / year	Variation/Average Earthquakes >M7.0/yr%
Pre-Nuclear Period	1900-1950	1132	22.6	-
Underground Test Period	1951-1996	814	18.1	-19.9
Post-Nuclear Test Period	1997-2003	105	17.5	-3.3

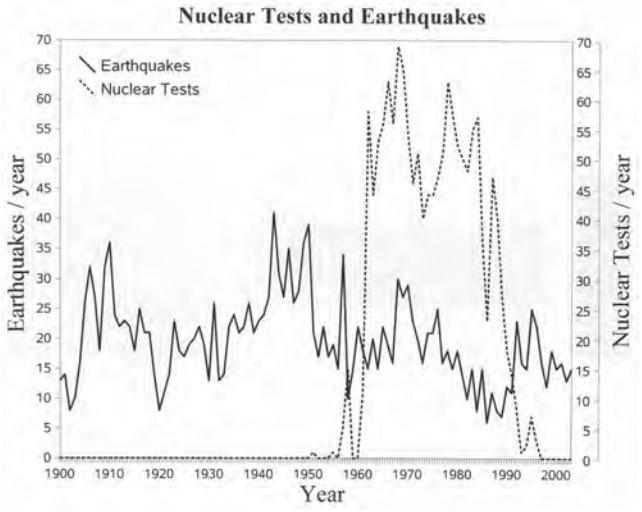

Figure 1. Nuclear tests and earthquakes 1900 to 2003. In this figure it is obvious that there is no increase of earthquakes with the begining of underground nuclear testing in 1951.

The analysed data in Table 1 and Figure 1 show a rise in rate of >M 7.0 earthquakes in the mid-1990s. At about the same time the rate of nuclear tests falls. This could be coincidence because the data represent only about 10 years.

Discussion

All data in this investigation indicate that there is no positive correlation between worldwide nuclear testing and worldwide major earthquakes with magnitude 7.0 or greater but a possibility of a negative correlation during the testing period. There is a rise in earthquake rate about 1995, but this rise looks no different to similar rises at 1905, 1940 and 1965 which don't happen to coincide with the end of nuclear testing. Thus, with this data it can be concluded that seismic waves, generated by nuclear testing, do not trigger worldwide major earthquakes with magnitude 7.0 or greater.

In his work Whiteford described the relationship betweeen nuclear testing and all earthquakes with >M5.8. He compared the earthquake rate before nuclear testing, and the nuclear testing time. Whiteford found a positive correlation. Before nuclear testing all earthquakes >M5.8 occured at an average rate of 68 per year, during the nuclear testing time 127 per year. This work show a positive correlation for a great range of magnitudes.

A possible explanation can be that artificially generated seismic waves and the following aftershocks lead to a reduction of tectonic stress within the seismic active region, and reduce the rate of major earthquakes with magnitude 7.0 or greater.

Further investigations and statistical tests could show if there is a negative correlation between worldwide underground nuclear testing and worldwide major earthquakes with >M7.0, and if artificial generated seismic waves can lead to a reduction of tectonic stress.

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A preliminary look at the influence of geological deposits in Britain and their use by our prehistoric ancestors

Gladys Dinnacombe

In the half a million years up to 4000BC, our ancestors had survived by gathering and hunting. But even during this time, outcrops of certain rocks and river deposits had influenced their survival. Archaeologists and scientists of many disciplines such as biology, geology and chemistry, have made great strides in the last twenty years, in the interpretation of the past (Table 1).

The first recognisable tools that we know of date back to around 2.5Ma. Much of the stone used for early tools probably came from stream and river beds where large hand-size pebbles could be found. These pebbles formed the most basic of tools and have been found at many archaeological sites. Signs of wear indicate the use of the tools; abraded edges show that these were most likely used as hammer stones, while smooth surfaces indicate grinding or polishing. Some pebbles have been modified for an easier grip or grooved to allow a handle to be inserted.

Makers of stone tools had to be aware of the physical properties of the various rock types with respect to the production of tools. Rock types varied from area to area and according to availability. Physical properties determined how well a cutting edge would last during prolonged use and how long a hammer stone could be used before it broke up. How easily rocks could be shaped was another factor and often people would have a choice between using poor quality local stone or trading from a distant source. This trade has been confirmed by the finding of tools made of stone which is not from a nearby area but often from much more distant places. Some areas showed that there had been large production of stone tools and quarrying or mining had been done.

Petrological examination can identify products of known 'factories' and can also lead to the acquisition of large amounts of data concerning the raw materials used, which in turn can lead to the discovery of previously unknown sources. Surveys of the petrology of British implements have lead to a list of petrology groups for stone axes. This is an ongoing survey. So far the survey has shown that a large proportion of stone tools used in an area are the products of a small number of factories, mines or quarries. Some of these are very large and their products are abundant hundreds of miles away. The Langdale axe factory is one such example.

Flint was a valuable resource for the manufacture of blades and points. The flint was mainly obtained from the Upper Cretaceous Chalk beds; the black flints of East Anglia and southern England being easily distinguished from the white flints of Yorkshire and Lincolnshire. The Upper Jurassic Portland chert is blue-grey and was used mainly in Mesolithic times in southern England. Black chert from the Carboniferous Limestone has also been found on Mesolithic sites. Flint tools at early sites are often derived from gravel deposits controlled by changes in climate.

Figure 1. Map showing the main areas of Stone Axe production.

In the Midlands, local quartzite was an alternative to flint, while greywacke has also been used for pebble hammers with shaft-holes. Such tools have been found and their source is the Coniston Grits of Silurian age. The range of rocks used for tools is limited and pebbles of these rocks are possibly more abundant because of their durability. Fine-grained rocks would also be easier to work by flaking than coarse-grained rocks.

Table 1 showing brief outline of different 'Ages' and human activity

c. 800 BC - 1st Century AD	Iron Age	
c. 2,500 BC - 800 BC	Bronze Age	First use of iron 1250 - 750 BC
c. 5,000 BC - *c.* 2,500 BC	Neolithic	Earliest use of metals c. 2500 - 2150 BC
c. 10,000 BP - *c.* 5,000 BC	Mesolithic	Ice age ends 10,000 BC, Britain separates from mainland Europe c. 6500 BC, first farmers c. 5000 BC
c. 500,000 BP - 10,000 BP	Palaeolithic	1st humans

Blades and points used as knives, saws, arrow or spear heads, awls and scrapers need to be sharp and precise so this puts a constraint on the type of rocks which could be used. Flint and other varieties of chert were most valuable for these kind of tools.

Axes and adzes could be used for felling trees, woodworking, hoeing and digging. Flint and chert were used and also greywacke further north. In some areas, tuff, such as the Borrowdale Volcanic Series and the Rhyolitic tuff of South Wales, was used for axes. The Whin Sill dolerite was also used and locally granodiorite was important. The Penmaenmawr axes were made of augite granophyre, the chilled margin producing a fine-grained rock worked by flaking then grinding. The above mentioned types of rocks are abundant in England and Wales. In Cornwall greenstones were used while hornfels was also widespread within the UK; Figure 1 shows places named in the text for axe production.

To return to flint; Grimes Graves is one of the interesting Neolithic sites in Britain. Grimes Graves, in Norfolk, is a flint mine which was worked between about 2200 and 2500BC. There are around 350 hollows in the ground which mark the location of former mine shafts. Some of these shafts are up to 10m deep. Horizontal galleries were dug along the seams of flint and when worked out, each shaft was filled with debris from the next shaft. Some of the workings are also of the open-cast type. A good quality flint, known as 'floorstone' is found here and the shafts were dug in order for this to be extracted (Figure 2). We do not know how the flint was taken to the surface, but recent excavations have indicated that wooden ladders were used to go up and down the shaft and bags or baskets used to carry the flint. Figures 3 and 4 show the inside of the mine.

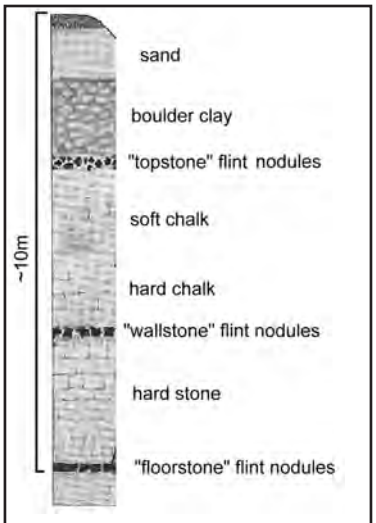

Figure 2. Vertical column through a pit at Grimes Graves.

Earlier flint mining (pre-4000BC) took place at Cissbury in Sussex. Here too, some of the shafts and pits can be seen. From evidence at these sites, it is concluded that it is unlikely that they were worked continuously, but only when a new supply of flint tools was required. There are other similar flint workings in Britain but in some areas such as Langdale and Penmaenmawr other rocks with fracture properties similar to flint have been worked. In the area around Langdale Pikes many small sites have been identified, some of which suggest open-cast working and others which suggest the working of large boulders in the scree.

The first appearance of metal tools and ornaments must have made a great impact on our ancestors. We do not know how metals were first introduced into Britain but we do know that early metallurgy can be found in south-east Europe around 5000BC. We also know, however, that metal objects were being made in Britain (and Ireland) before 2000BC. Tin-bronze began to be used only 400 years after the introduction of copper-using technology. The earliest objects were of pure copper but tin and arsenic were

Figure 3. Flint seam in Grimes Graves [probably the floorstone, the lowest seam]; photograph © Jane Clarke.

then added to produce bronze. But, before any such objects could be made, the ore itself had to be found, mined or quarried, then smelted more than once, before combining with tin. It was eventually moulded or cast, followed by shaping or decorating. Ore sources were widely scattered as shown in Figure 5. The metal artefacts produced were mainly axes, daggers and spearheads.

Bronze Age copper mines are mainly found in Wales and Ireland. The best known of those in Wales is the one situated on the Great Orme in Llandudno. Possible sites in England are Alderley Edge and Ecton (in the Peak District). Although copper and tin have a long mining history in Cornwall, there is no evidence to support mining in the Bronze Age although there may have been alluvial extraction of tin at that time. It is possible that these sites and others may have had their earlier mining history obliterated by later mining operations.

The use of stone for tools may have led to the discovery of outcrops mineralised with malachite and azurite and may have led to the use of these minerals. Mining in the 18th and 19th centuries led to the discovery of much older workings, some of which were destroyed. In the earliest metal mining, bronze tools were not used but stone and bone tools were common. Once a deposit had been discovered the Bronze Age miners were able to follow the minerals underground. Bronze Age mines are usually of the open-cast type or surface pits where narrow trenches could be made or inclined drift openings. However, underground mining is also known, the classic example being the Great Orme copper mine which is now open to the public.

Figure 4. Working gallery in Grimes Graves. Height ~1m; photograph © Jane Clarke.

Figure 5. Map showing the main copper mining areas in the Bronze Age.

In the Great Orme mine the mining was on a large scale and to date covers an area of around 6 acres and reaches a depth of around 70m from the surface. Bronze chisels have been found, as well as hundreds of stone hammers. The excavation work on the mine has shown that the Bronze Age miners followed the softer parts of the vein. Radiocarbon dating has shown that mining here covered a span of around 1000 years! To extract the ore, a combination of fire setting and stone hammers was used, although fire setting was not used often in the Great Orme mine. Fire setting is a technique of rock extraction found worldwide. It involves burning wood fires against the rock face, causing it to weaken. In some cases, the rock was then quenched with water making it easier to remove. It is also known that these early mines took advantage of any fractures, joint planes or cleavage in the rock.

The main copper minerals in the Great Orme mine were malachite and chalcopyrite. The geology of the Great Orme has been covered in an article in the OUGS Journal 19(1) but in this particular area, the limestone is dolomitised and interbedded with bands of soft shale. Once the ore was removed, the mineral had to be extracted from any rock surrounding it. This could then be smelted, reducing it to metal. There is evidence that this was done by first of all crushing the rock using stone hammers and anvil stones then sorting to collect the fragments of mineral. There is very little archaeological evidence of the smelting of copper and it has been suggested that smelting may have taken place at low temperatures which would have produced very little slag, which would be difficult to recognise. Another suggestion is that smelting may have taken place elsewhere.

It is known that metal-working was taking place at the same time as the final Stone Age phase as a bronze axe found in Dorchester was dated to 2300BC. Copper melts at 1083°C and this can be achieved in a small open bowl furnace with charcoal as a fuel. The heat can be obtained by using bellows to create a strong draught. The molten metal collected in the bottom of the bowl furnace and would then cool to form a block. This could then be reheated in a crucible made of clay until it melted and then poured into a mould. Moulds could be made of clay or stone. Complicated objects could be made in piece moulds, some of which looked like a bivalve. Sometimes small channels were made in the mould to allow trapped gases to escape. Moulds for swords have been found. Making a sword required more skill than casting a dagger or an axe due to its size.

Small solid objects could be made using the lost wax method. A wax model was made, then covered in clay. The wax was then melted out and molten bronze poured into the hollow which was left. After the metal solidified, the outer clay was removed. Larger objects could be made by core casting. The rough shape of the object was made in clay, then covered in wax keeping the shape, then another layer of clay was formed around it. The wax was melted and the molten metal poured in the space left. When the metal was solidified, the outer clay was removed and sometimes the inner clay as well, leaving a hollow object.

Copper and bronze was easily shaped by hammering. The techniques of annealing and quenching were also used and simple lathes removed irregularities or pressed metal around a mould. Pieces of bronze were joined together with rivets which were short metal rods passed through holes in metal plates then hammered down. There were many ways of working designs; engraving, overlays, inlays, and repoussé work. Engraving, overlays and inlays are self-explanatory while repoussé is where the design is in relief and the background depressed using a hammer or a punch.

The use of iron was introduced into Britain around 700 BC. It was probably imported from Europe into the Thames Valley area where it was worked into local forms and distributed. As production increased, iron became cheaper and enabled the smelting of our own ore.

The furnace technology was similar to that of copper, so iron could be produced in copper smelting furnaces. There was early iron smelting in Chinnor, Bucks and Mucking, Essex, although these are not usually considered to be iron-ore bearing areas and small workable deposits of iron ore were readily available throughout Britain. There were three main types of ore:

a) carbonate -the most common, occurring as nodules in the Coal Measures and the Wealden Series or as sedimentary deposits in Northamptonshire and Lincolnshire in the Oxford Lias

b) hematite

c) limonite

With carbonate ores, the iron is present as ferrous carbonate, $FeCO_3$, and when the ores are roasted, carbon dioxide is driven off as in lime burning and ferrous oxide (FeO) left. Further roasting converts FeO to magnetite (Fe_3O_4) or to ferric oxide (Fe_2O_3), which are chemically the same as hematite.

With the nodular form, sometimes called argillaceous or clay-ironstone, the nodules can be any size from a few cms. in diame-

ter up to a metre. Bands of nodules are commonly found in Coal Measures where they appear to have been formed by crystallization, in surrounding shales. The nodule bands normally underlie the coal and may often appear where coal seams outcrop.

The Jurassic scarp from the Cleveland Hills into Oxfordshire is another source of carbonate ores. Surface deposits sometimes weather in some places to limonite, magnetite or hematite.

Hematite ores (Fe_2O_3) occur mainly in Cumbria and in the Furness area.

The limonite group of ores is found in the Forest of Dean and along the edge of the South Wales coalfield. Limonites are hydrated iron oxides and consist mainly of crystalline oxide geothite ($Fe_2O_3.H_2O$ or FeO.OH) with varying amounts of absorbed water.

Iron ore also occurs in the copper deposits of Alderley Edge, Weardale, the Mendips and in the Leadhills, area of Lanarkshire. The best ore for smelting is not necessarily that with the highest iron content but one with a high iron to gangues ratio. Gangue minerals such as silica, calcia and alumina are slagged off during the smelting process and take a proportion of iron (as a flux) with them during the formation of the slag.

Iron requires strong reducing conditions in the furnace. Iron has a higher melting point than copper. Iron can be reduced at approximately 800°C. well below the melting point of 1540°C. Most iron ores are rarely pure so impurities not removed by washing must be removed by slagging at high temperatures (more than 1100°C)

As iron is produced below its melting point, it is in a solid state as a sponge or raw bloom composed of a mixture of iron and slag. This bloom has given its name to the technique known as the 'blooming process'. Any slag still trapped can be removed by liquation, the smelting process at or above the temperature that allows slags to drain away from the solid iron. This occurs about 1150°C. Any slag remaining is gradually removed during the forging process when it is squeezed out by the cycle of reheating and hammering.

The early iron smelter was fuelled by charcoal with oak being the main source until the 13th century when there was a shortage of timber.

Complete furnaces are rare in the archaeological record but we know of bowl furnaces, shaft furnaces developed from the bowl furnace and slag pit furnaces. (Figure 6) The presence of large quantities of slag or tapped slag run from the furnace and prepared and roasted ore, suggest smelting on a site. No furnace slag or slag remains have been found which can be dated before 500BC. Large quantities of slag found imply a bloomery. Tap slag, slag that has leaked or been allowed to run from a furnace in a semi-molten state, indicates smelting.

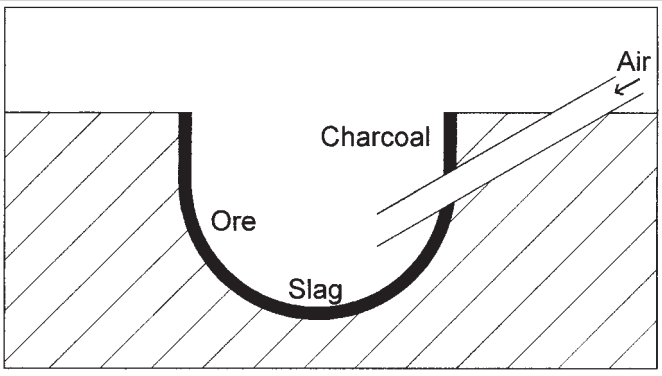

Figure 6. Sketch of a bowl furnace.

In the late Bronze Age, Brooklands near Weybridge, produced the first of 21 furnaces in use up to the Roman period. The most complete furnace is bowl shaped with a superstructure of red clay. Twelve furnaces had a diameter of 30-35cm and were probably bowl furnaces with low shafts. Another six were over 60cm in diameter and most likely were reheating hearths for forging.

Cow Down, Longbridge Deverill, Wiltshire, has material dated to the same period and has several furnace bottoms but no furnace structures. There are many other sites which have yielded furnace remains.

There are many iron artefacts but some worth mention are the so-called 'Currency' bars found mainly in the south of England. There are two types: 1) tapered sword shaped bars and 2) parallel sided bars almost all having a socketed end. Most have been dated to between the 1st century BC and the end of the 1st Century AD. They are often found in hoards. It has been suggested that the bars are semi-finished swords and would have some value.

Early Iron Age swords have lengths of 81-90cm, a length similar to that of the currency bars which is consistent with the above suggestion.

The techniques of casting, hammering and rivetting continued from the Bronze Age into the Iron Age and the welding of iron also became important. The tools made in the Iron Age and used in ironworking are virtually the same as those used today by a blacksmith. Iron was a valuable commodity and even small items made of iron were highly prized. Experimental archaeology has shown that the Iron Age techniques still work today. A modern blacksmith works in the same way as a smith in the Iron Age.

Tools such as knives were around 15-20cms long with a handle made of bone, wood or perhaps antler. Razors for shaving have been found as well as many tools for woodworking such as adzes, awls, gouges, saws and files. The ability to work with iron enabled better agricultural implements to be made and these include socketed reaping hooks, sickles, bill hooks and ploughshares.

Iron fittings included nails, iron dogs, latchlifters, rings, studs and bucket bindings while iron jewellery, personal ornaments, harness and chariot fittings, weapons, cauldron chains, tripods for suspending cauldrons were also made.

Weapons and armour included daggers, hilt guards, pommel bars, iron swords with bronze hilt guards, and socketed spearheads. Because iron rusts away, it has been often difficult to find good artefacts which can be dated accurately and which give evidence of how they were made.

This is an introduction to what I hope will be a much longer article. I feel that we underestimate our ancestors. They were able to use stone and metals in ways that enhanced their lifestyle using methods that we would find difficult today!

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Book reviews

Cornwall's Geology and Scenery 2nd Edition by Colin M Bristow, 2004, Cornish Hillside Publications ISBN 1900147386 (paperback) £14.99, ISBN 1900147394 (hardback) £18.99.

My evening class and Open University geology students are fascinated by the history of the Earth beneath our feet. They want to understand why different rocks and minerals are found where they are and to know how they were formed and how they got there. They are enthralled to know that the rocks of Cornwall formed in environments ranging from tropical seas to volcanic eruptions, and from deep ocean floors to mountain ranges. Every new group I teach particularly wants to know where they can find more about their local Cornish rocks and Professor Bristow's book is one that I've recommended since it was first published as it is particularly readable and accessible to enthusiastic amateurs.

An early section on "useful concepts" provides a mini-geology-course to help the reader understand the tale of Cornwall's geological history. This story unfolds through the following chapters which explain the successive processes that produced the slaty cliffs and granite moors, formed the serpentine that is carved on the Lizard and the china clay that is the basis of our major industries and exports. There are excellent "step-by-step" diagrams and the reader is guided to the best places in the Duchy to see the evidence for themselves.

However, good though the first edition was, ours is an exciting and dynamic science and continuing mapping by the British Geological Survey and research by Earth scientists, plus improvements in the technology for examining, analysing and dating rocks, mean that this is a story that doesn't stand still! The author recognised that seven years on there were areas that would benefit from revision. In particular he has updated and expanded the "Curious Tale of the Lizard" – which tells how a great chunk of "fossil" ocean floor was lifted several kilometres and incorporated into the rocky crust of our continent. He has also extended the description of conditions in Cornwall and the way the landscape evolved during the ice ages – food for thought in the climate change debate?

The presentation has been improved: there are more photographs, over half of these now in colour whilst the remaining B&W illustrations are clearer; tables are updated, there is more text, an expanded index and additions to the list of further reading.

This is a book that will give added depth to any country-lover's knowledge and understanding of the Cornish landscape. It is available through local booksellers, from Tor Mark Press, United Downs, St Day, Redruth TR16 5HY (01209 822101) or sales@tormarkpress.prestel.co.uk or can be ordered online from Willow Books www.willowbooks.co.uk

Linda Fowler OUGS Tutor

Stereographic Projection Techniques for Geologist and Civil Engineers by Richard J Lisle, Peter R Leyshon, 1 April 2004, Cambridge University Press, 112pp, £19.99 (paperback) ISBN 0521535824 £50.00 (hardback) ISBN 0521828902

Stereographic Projection is a subject that was not covered during my OU studies. I first came across it when using the Earth Science Consortium software. The aim of this book is to provide a simple introduction to the subject and its underlying principles and is written for undergraduate structural geology students. The technique exploits the outcome of a two-stage process of the projection of lines or planes onto a sphere and the resulting points and great circles being projected onto a flat piece of paper. This procedure results in a flat representation of three-dimensional orientations – a stereogram.

The book takes the student through well-presented sections using pairs of facing pages; text on the left and diagrams to the right. The examples used are straightforward and very easy to use. A few introductory pages review geological structures and their measurement before the authors move on to the meat of the subject – using stereographic projection to interpret field data. Early examples move from the plotting of planes through to the analysis of folds and onto calculations concerning movement on faults. As the examples become more advanced, the techniques covered range from the plotting of cones, rotation about horizontal and inclined axes, the restoration of tilt of beds, the restoration of palaeocurrents and the analysis of more complex folds. The final sections have a more geotechnical content, being concerned with rock slope stability and associated problems. The examples are well-supported with two sets of exercises at suitable points in the book. A set of appendices provides examples of various stereographic nets, a fold orientation classification chart and a set of useful formulae. In addition to a comprehensive reading list, the authors also provide a list of authors of computer programs for plotting and analysis of orientation data.

Providing a method for three-dimensional data to be represented and manipulated, stereographic projection is a tool that assists the geologist to visualize three dimensional problems. With this work the authors have provided a simple and easily useable introduction to the subject. If you have an interest in structural geology, this book is an ideal aid.

Mike Hermolle, BSc (Hons) Natural Sciences (Open)

Volcanic Instability and Tsunami Generation: Montaña Teide, Tenerife, Canary Islands (Spain). Project Report for SXG390 – Geohazards

Gerard A Vallely

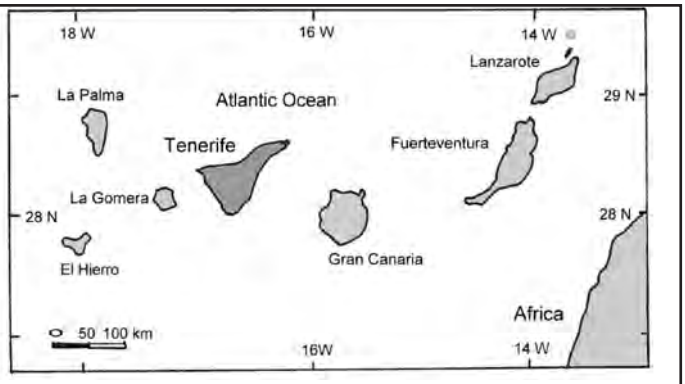


Figure 1. Location of the Canary Islands.

Abstract

In the Atlantic Ocean a group of volcanic ocean islands, the Canary Islands, show evidence of edifice failure. Different phases and styles of edifice failure are seen on the islands of El Hierro, La Palma and Tenerife. On the sea floor, adjacent to the islands, there are debris aprons similar to those seen off the Hawaiian Islands. The Canarian Islands of La Palma and Tenerife have massive landslide valleys. Recent volcanic activity (within the last 500 years) has occurred on four of the islands. All the historical activity has been from vents associated with rift zones. Canarian rift zones appear to have either single or triple arms. The northern flank of Tenerife and the volcanic edifice of Montaña Teide are unstable and in the early stages of failure. Such failure will be catastrophic as collapse of the edifice will generate a massive gravitational landslide which in turn will generate a massive or "mega-" tsunami when the debris enters the Atlantic Ocean. This will cause massive devastation on the nearby islands of El Hierro, La Gomera and La Palma. The other Canarian Islands and the African mainland will also suffer large-scale destruction. The European Atlantic seaboard including the British Isles, Iceland and Greenland, together with the eastern seaboard of North America and islands in the Caribbean will be affected by surges estimated to be in excess of 30m high. The potential hazard has the ability to cause a horrific loss of human life. The infrastructure of the islands will require total rebuilding and will take several tens, if not hundreds, of years to accomplish. The financial cost will also be extremely high, possibly billions of $US.

Introduction

The awesome spectacle of the lateral blast, explosion and plinian eruption of Mount St Helens in the Cascade Ranges, May 1980, provided dramatic visual evidence that volcanic edifices can fail and generate massive debris flows.

Prior to the Mount St Helens eruption Moore (1964) had interpreted features shown on the nautical chart around the Hawaiian Islands, as debris flows related to features on the islands of Molokai and Oahu. He was able to demonstrate that the features were neither a volcanic ridge nor the remains of an eroded landform. The largest flow exceeded 160km in length, was ~50km wide and estimated to be ~2km thick (Figure 3a, 3b).

Amongst the volcanic ocean islands in the Atlantic basin is the Canary Islands archipelago (Figure 1) which comprises seven large and two smaller inhabited islands, and several small islets (Araña 1995). They range from about latitude 26° to 30° North and between longitude 13° to 18° West. As a general rule the islands are oldest in the east and the youngest island, El Hierro at the south-west end of the archipelago, is a young shield volcano. Historic (15th Century to date) volcanic activity has occurred on El Hierro, Lanzarote, La Palma and Tenerife (Carracedo 1996). Activity on all the islands has been from rift systems which erupt basaltic lavas (Carracedo 1996).

Tenerife is the largest island and resembles an isosceles triangle approximately 80km long and 40km wide, rotated about 45° to the east (Plate 5 centre pages). The island is surmounted by the strato-volcano Montaña Teide 3718m, which rises some 1500m above the floor of the Las Cañadas Caldera. The origin of the Las Cañadas Caldera is the subject of ongoing debate and research. The remains of the original basaltic shield volcanoes form the apexes of the island: Anaga – north-east apex, Teno – north-west apex and the Roque del Conde – at the south apex (Fúster *et al*. 1968). Radiating out from these three apexes are three arms of a rift system. The three arms meet in the Las Cañadas Caldera and form a triple junction (Figure 2). Two arms of the rift are volcanically active with seven historic eruptions associated with vents at various locations. As a result of volcanic activity associated with the rift, the northern flank of Tenerife is potentially unstable.

In this report the processes that cause volcanic edifice failure and the associated potential hazards are examined. The volcanic edifice of Montaña Teide on Tenerife is then examined and evidence is presented demonstrating how the processes that cause volcanic edifice failure are affecting Montaña Teide and making it unstable. A model is presented showing how the deformation is affecting the instability of the edifice and the potential hazards that edifice failure would cause. The hazard is quantified in terms of loss of life and property. Methods of monitoring the edifice are discussed. Finally, methods of mitigating the hazard are discussed.

Literature Review

The awesome spectacle displayed by Mount St Helens when it exploded in May 1980, revealed the previously unrecognised phenomena of volcanic edifice failure. The northern flank failed in a massive landslide, which resulted in a lateral explosion that uncovered the magma chamber and caused a plinian eruption. From the first motion of the northern flank to the actual eruption was about 25 seconds (Daniels 1982). The resulting debris avalanche travelled 23km in ~10 minutes at an average velocity of ~38ms^{-1} and covered more than 550km^2, to an average depth of 45m. One lobe of the avalanche caused a mini-tsunami on Spirit Lake, causing the wave to rise 260m (Voight *et al.* 1983) above the pre-eruption level of the lake of ~975m (A C Nisbit pers com. 2003). It was considered to be a relatively small eruption, with a Volcanic Explosive Index (VEI) rating of 5 (Boer & Sanders, 2002).

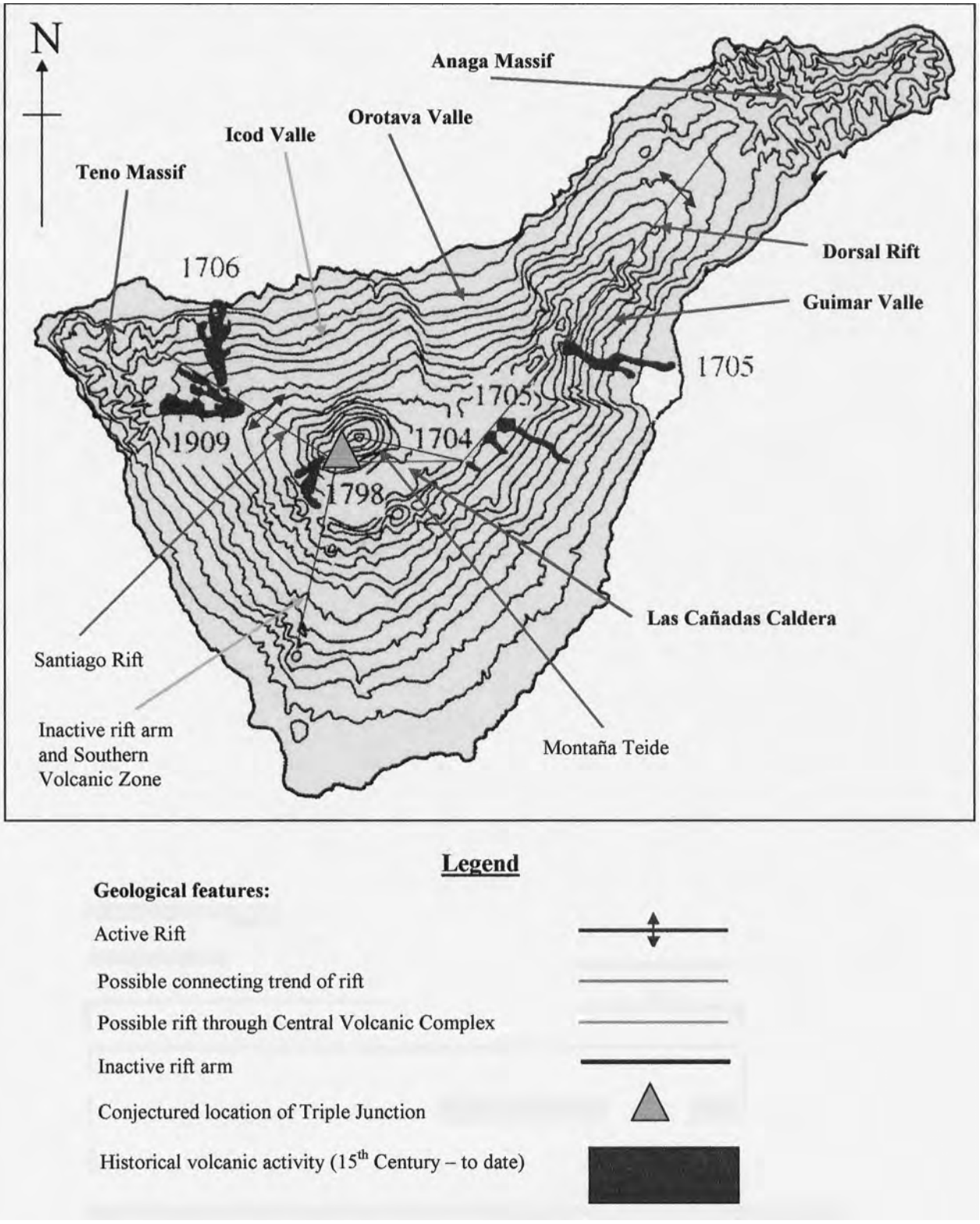
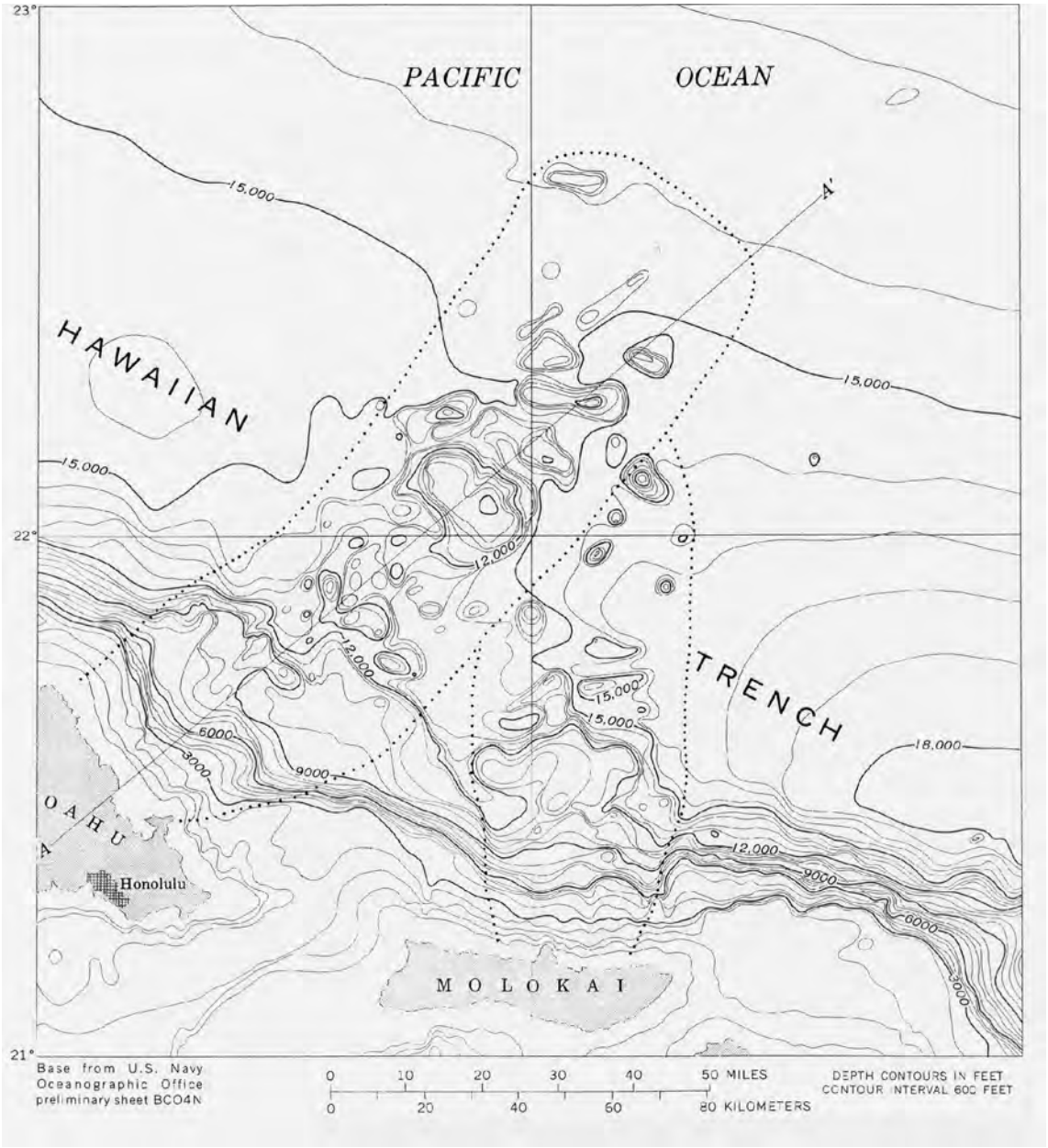


Figure 2. Tenerife with the volcanic features added. All the historical (15th Century to date) volcanic activity – dark grey, has been associated with the two active rift arms. The 1706 eruption destroyed the town and principal port of Garachico. Map based on Carracedo 1996. (GAV 12-03-2003)

Almost 20 years earlier, edifice failure was postulated as the cause of sinuous features on bathymetric charts around the Hawaiian Islands (Moore 1964). The charts showed two large features that extended from the islands of Molokai and Oahu (Figs. 3a & 3b). The largest exceeded 160km in length, ~50km wide and was estimated to be ~2km thick (Moore 1964). Moore (1964) was able to demonstrate that the features were neither a volcanic ridge nor the remains of an eroded landform.

As a result of the explosion at Mount St Helens, volcanic edifices around the world were examined by volcanologists operating under the auspices of the United Nations (UN) as part of International Decade for Natural Disaster Reduction. This result-



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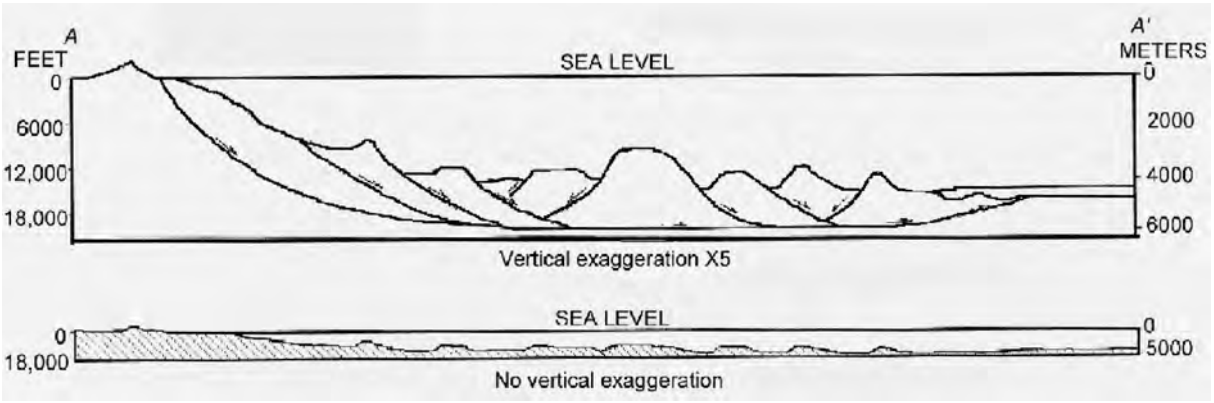

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Figure 3. a). Part of the US Navy bathymetric chart around the Hawaiian Islands showing the two large landslides – dotted lines, that Moore (1964) interpreted as being the result of mass wasting of the volcanic edifices of Molokai and Ohau. The younger slide from Oahu, which extends for over 200 km, crosses the Hawaiian Trench and continues across the abyssal plain to the north-east of the trench. (Moore 1964); b) . Section A – A' showing the landslide debris from Oahu. Note the rotation of the blocks and curved failure plane on Oahu. These are characteristic features of all landslides. Indicative of the high levels of kinetic energy and almost frictionless motion is the length of the Oahu slide ~210 km, the large kilometre sized blocks and the thickness of the slide ~2 000 m (Moore 1964)

ed in Montaña Teide being classed as the 13th most dangerous volcano in the world (NASA 1994; IAVCEI 1998). Following those investigations it is now recognised that all volcanic ocean islands have undergone edifice failure (McGuire 1996).

Amongst the volcanic ocean islands in the Atlantic basin is the Canary Islands archipelago comprising of seven large and two smaller inhabited islands, and several small islets (Araña 1995). They range from about latitude 26° to 30° North and between longitude 13° to 18° West. As a general rule the islands are oldest in the east; the youngest island El Hierro, at the SW end of the archipelago, is in the shield-building stage. Historical (since the 15th Century) volcanic activity has occurred on El Hierro, La Palma, Lanzarote and Tenerife. El Hierro, La Palma and Tenerife all display evidence of mass wasting due to edifice failure (Carracedo 1994).

Tenerife

Figure 4. Panoramic view of the Las Cañadas Caldera showing the strato-volcano Montaña Teide (3718 m) and on its lower right flank the associated cone of Montaña Blanca. The Las Cañadas Caldera is visible between Teide and the caldera wall. The line of rocks in the middle foreground between the dark lavas and the caldera wall are the Roques de Garcia which some workers consider mark the boundary between the Ucanca caldera to the left and the Guajara – Diego Hernandez caldera to the right. The prominent peak on the caldera wall is the Guajara peak - 2717 m. North is approximately on a line extending from Guajara to Teide. (Anon – from a postcard)

Tenerife is the largest island in the archipelago with a surface area of ~250km^2. It resembles an isosceles triangle that has been rotated about 45° to the north-east (Plate 5). The island is surmounted by the strato-volcano Montaña Teide 3718m above sea-level (ASL) and its neighbour Pico Viejo - 3072m (Figure 4). There are three massive gravitational landslide valleys - two on the northern flank and one on the southern flank of the island.

Montaña Teide and Pico Viejo

The strato-volcano Montaña Teide is the highest point in the Canary Islands. Montaña Teide together with Pico Viejo and Montaña Blanca, form the central volcanic complex on Tenerife. Eruptions from these three volcanic vents are explosive due to the high viscosity of the magma which has evolved in a shallow (about sea-level) magma chamber. Associated with the central volcanic complex is the Las Cañadas Caldera (Figure 4).

The Las Cañadas Caldera comprises a lower (Ucanca) and an upper (Guajara) caldera (Figure 4). The height difference between the upper and lower calderas is ~200m. The origins of the caldera are strongly debated. At several locations within the Ucanca Caldera, vertical dykes approximately parallel with the southern wall of the caldera are seen. Martí *et al.* (1997) consider that these vertical dykes are a ring dyke and therefore prove the existence of a collapse caldera. Ancochea *et al.* (1998, 1999) consider that the vertical dykes are related to an avalanche caldera and that the caldera wall is the eroded head wall of a massive landslide valley.

Canary Islands Bathymetric Data

Bathymetric surveys carried out near the Canary Islands show the presence of submarine features similar to those found around the Hawaiian Islands. These are interpreted as indicating that the Canary Islands have been subjected to mass wasting (Holcomb & Searle (1991), Weaver (1991), Weaver *et al.* (1992)). A 1997 scientific investigation of the ocean around the Canary Islands has added further data to the earlier bathymetric surveys. The 1997 survey mapped the submarine parts of all the islands and adjoining sea floor (Rihm *et al.* 1998). The survey identified many debris avalanches: some blocks were over 1km in diameter and had been transported over 20km from the coast. Many of the debris flows extended for more than 150km.

Tenerife Gravity Data

MacFarlane & Ridley (1968) demonstrated that a three-armed formation in the local Bouguer gravity anomaly coincided with topographical high ground on Tenerife. Results from later gravity surveys have been interpreted as indicating a large anomaly beneath the Southern Volcanic Zone (SVZ) (Füster *et al*. (1994), Araña *et al.* (2000), Ablay & Kearey (2000)). The SVZ is considered to be volcanically inactive and acting in the manner of a buttress (Carracedo 1994, 1996). Huertas *et al*. (1994) claim that the gravity anomalies have influenced the structural development and volcanic activity of Tenerife.

Rifts

Tenerife has a three-armed rift (Carracedo 1994, 1996) (Plate 5 & Figure 2). All historical eruptions have been associated with the NE – SW and NW – SE arms of the rift. The third arm is volcanically inactive and acts as a buttress (Carracedo 1994, 1996). Field evidence demonstrates multiple intrusions of vertical dykes. Siebert (1984), Elsworth & Day (1999), Elsworth & Voight (1996) and Gudmundsson *et al.* (1999) showed that the intrusion of dyke swarms increases the local stress field creating failure planes perpendicular to the dyke swarm. The failure planes increase in severity with each intrusion. At some stage the whole mass fails, generating a massive gravitational landslide valley (Hürlimann *et al.* 2000). The Dorsal Rift on Tenerife is associated with three massive gravitational landslide valleys – Güimar, Icod and La Orotava have formed perpendicularly to the Dorsal Rift (Figure 2). Walter & Troll (2003) showed that a rift can be modified by flank-creep on a volcanic edifice.

Landslides

The mechanics involved with the generation of landslide valleys are poorly constrained. Siebert (1984) showed that the intrusion of parallel dyke swarms ultimately caused landslide valleys to form perpendicularly to the dyke swarms. Several workers e.g. Watts & Masson (1995), Hürlimann *et al.* (1999), Ablay &

Hürlimann (2000), Hürlimann *et al.* (2000), have shown that the northern flank of Tenerife has evolved to its present state by the generation of massive landslides induced by the intrusion of dykes into the adjacent rifts. Slope failure need not be instantaneous, as demonstrated by the San Andres fault system on El Hierro which initially moved "… Few tens of metres …" (Day *et al.* 1997). It stalled for several thousands of years before undergoing rapid movement in the order of 300m.

Day *et al.* (1999) have shown that comparisons made between the Canary Islands and Hawaiian Islands are not as robust as may be expected (Carracedo 1999). The average edifice slope on the Hawaiian Islands is 5-10° whilst the Cumbre Vieja and Teide are inclined at 15° to over 20° (Day *et al*. 1999). The potential for large-scale gravitational landslides is greater on La Palma and Tenerife than the Hawaiian Islands.

Calderas

Williams (1941) claims there are two basic types of caldera: collapse calderas and avalanche calderas also known as sector collapse.

Collapse calderas consist of a roughly circular mass bounded by a ring fault which has dropped more or less vertically into the void of the vacated magma chamber (Figure 5). Any residual magma is forced out of the chamber upwards along the fault line and once solidified forms a ring dyke Clough *et al.* (1909). The generation of collapse calderas within active volcanic centres has been reported by Duffield *et al.* (1982), Guest *et al.* (1984), Hallinan & Brown (1995) and Geshi *et al*. (2002). Geshi *et al.* (2002) described the formation of a collapse caldera during an eruptive phase of the Miyakejima volcano, Japan, indicating that such processes can be syn-eruptive and not just a phenomena that occurs in the final stages of an eruption. Carracedo (1994) showed that in the Canary Islands, collapse calderas formed near to the triple junction of three-armed rifts and are located within the two active arms.

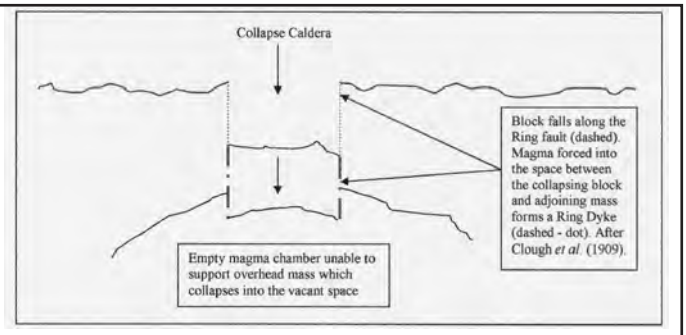
Collapse Caldera
Block falls along the Ring fault (dashed). Magma forced into the space between the collapsing block and adjoining mass forms a Ring Dyke (dashed - dot). After Clough *et al.* (1909).
Empty magma chamber unable to support overhead mass which collapses into the vacant space

Figure. 5. The basic principle of the formation of a collapse caldera. The underlying magma chamber empties at a higher rate than replenishment and is unable to support the overlying edifice. This collapses catastrophically and creates a collapse caldera. (GAV 21.08.2003)

Avalanche calderas have a characteristic "horseshoe" plan with an amphitheatre at their head, (Plate 5 left). Other characteristics include: listric failure plane (Figure 6), headwall sub-parallel to an active rift, sidewalls that are approximately parallel, they form on slopes where the inclination is at least 20°, failure of the rock mass can occur suddenly, the failed mass becoming highly mobile

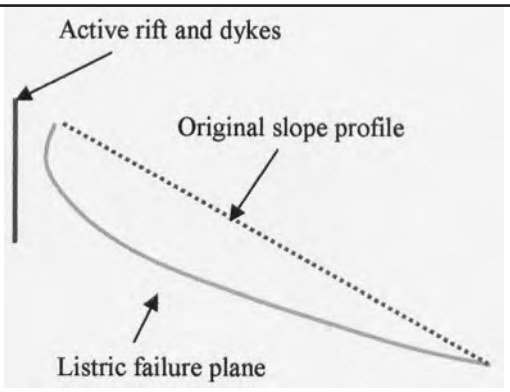

Figure 6. Schematic showing the characteristic listric shape of avalanche calderas. This profile is typically associated with landslides and is seen in the Guimar, Icod and Orotava valleys on Tenerife (Drawn GAV 18.09.2003).

and has the characteristics of a liquid, rapidly covering long distances (Siebert 1984).

Las Cañadas Caldera

The origin of the Las Cañadas Caldera is strongly debated. Martí *et al.* (1997) claim that the caldera formed as a true collapse caldera (Figure 5). Due to erosion and volcanic activity, much field evidence indicating how the caldera formed is absent. The absence in places of the caldera wall adds to the controversy. MacFarlane & Ridley (1968) did not detect a gravity anomaly under the Las Cañadas Caldera. Carracedo (1994) claimed that the Las Cañadas Caldera was the result of the generation of a massive landslide valley which resulted in the Icod Valle. Carracedo (1994) based his claim that the Las Cañadas Caldera was, at least in part, the upper zone of a landslide valley, on the occurrence within the subsoil of the caldera of "… altered, plastically deformable, clay-rich explosive breccia formation …".

Using evidence from boreholes sunk in the caldera, Martí *et al.* (1997, Martí & Gudmundsson 1998) interpret the vertical dykes which are approximately parallel to the caldera wall as evidence for a ring dyke. They demonstrated that the depth of eruptive material within the Las Cañadas Caldera is deeper than any projected pre-Teide eruption land surface in the Icod Valle (Figure 7). All the rocks recovered from borehole B1, which is 510m deep, originated from Montaña Teide and Pico Viejo (Ablay & Martí, 2000). The depth of borehole B1 and the elevation of Guajara 2717m, ~600m above the caldera floor, indicates a minimum subsidence of ~1100m (Martí *et al.* 1997, Marti & Gudmundsson 1998).

Ancochea *et al.* (1998, 1999) claim that the evidence presented by Martí *et al*. (1997) is erroneous and cite the absence of the north-

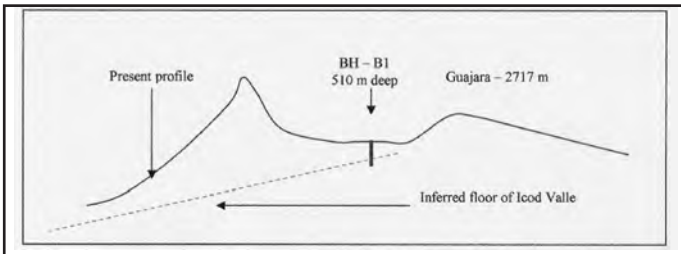

Figure. 7. Interpretation of data from Bore hole B-1 in support of the claim that the Las Cañadas Caldera is a true collapse caldera. (Martí *et al*. 1997, Marti & Gudmundsson 1998). (GAV 10.09.2003).

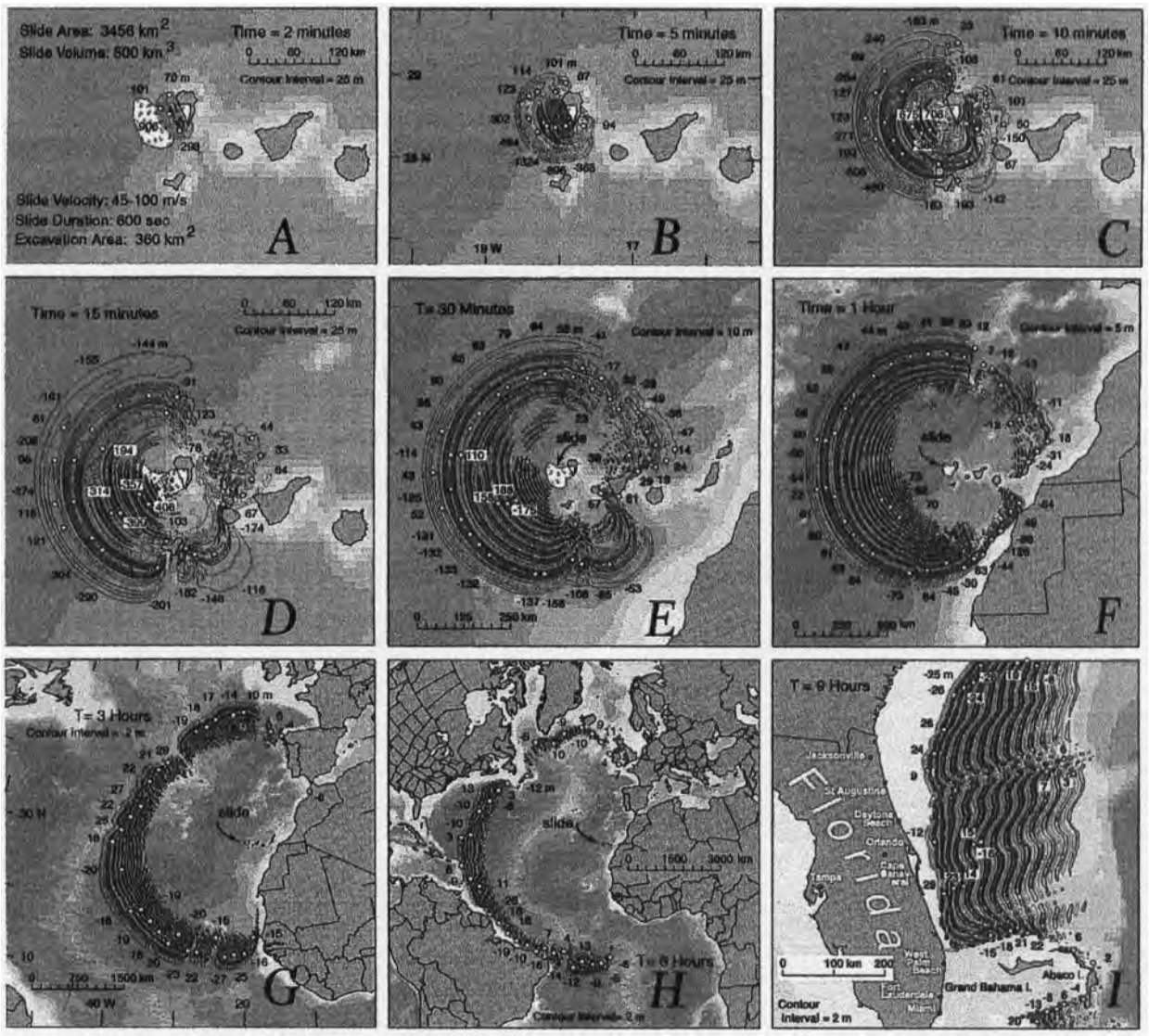

Figure. 8. Computer-generated images showing the effect of flank failure of the western flank of the Cumbre Vieja. Of importance to this report is the modelling of the tsunami affecting the eastern shores of La Palma and the islands of La Gomera and El Hierro – frames C & D. Frames D, E & F indicate that in less than 1 hour almost all the islands in the Canarian archipelago will have been affected by the tsunami. The La Palma model can be applied to Tenerife with some modifications, but also serves as an indication of what may occur when the northern flank of Tenerife collapses. (Ward & Day 2001)

ern sector of the caldera wall as confirming that the Las Cañadas Caldera owes its origin to a gravitational landslide. They also cite the evidence displayed in the Guimar and La Orotava valleys' headwalls as indicating the same phenomenon as the Las Cañadas Caldera wall. They interpret the vertical dykes that are approximately parallel to the caldera wall as ordinary vertical dykes and not ring dykes.

Tsunami generated by edifice failure

The oceans absorb and store massive amounts of kinetic energy usually from winds. The only phenomenon that is able to disturb the whole water column is a tsunami, usually generated by tectonic activity affecting the ocean floor. Seismically induced tsunamis are generally no higher than ~10m, (Tappin 2001). They propagate at ~300ms^{-1} and are generally unnoticed on the open waters of an ocean due to their long wavelength and low amplitude.

Tsunamis generated by volcanic edifice failure have the potential to be far larger than any seismically induced tsunami (BBC2 TV 2000). The western flank of the Cumbre Vieja on the adjacent island of La Palma is in the initial stages of failure (Day *et al.* 1999, BBC2 TV 2000). Modelling indicated that the wave would attain a height of ~600m and propagate westwards from La Palma (BBC2 TV 2000.). More recent modelling indicates that the wave would propagate omni-directionally and devastate the other islands in the Archipelago along with much of the western seaboard of Europe including the British Isles (Figure 8), (Ward & Day 2001). The model indicates that the initial wave will have a peak to trough height of ~2km and is indicative of the minimum size that a tsunami caused by the collapse of Montaña Teide would be. Montaña Teide is ~2000m higher than Cumbre Vieja and the gravitational acceleration is therefore greater, resulting in higher kinetic energy and velocity as the debris enters the ocean.

Evidence for a volcanically induced tsunami comes from the Italian volcanic island of Stromboli in the Mediterranean Sea. On the western flank of Stromboli is the Sciara del Fuoco (The Fire Scar). On 30th December 2002, an eruption triggered a landslide

down the Sciara del Fuoco of an estimated $5x10^6$ m^3. This entered the Mediterranean Sea and generated a local tsunami which severely damaged parts of the infrastructure and property on the island. No lives were lost, though some people sustained minor injuries. It is estimated the damage will cost several million euros to repair. (Stromboli website).

Discussion

Edifice failure within the Canary Islands presents a serious potential hazard to proximal and distal locations. Day *et al.* (1999) showed that a future collapse of the Cumbre Vieja would generate a tsunami which would radiate outwards and devastate coastal areas of North America up to 25km inland. Ward & Day (2001) have refined the model of Day *et al*. (1999) for a tsunami generated by the Cumbre Vieja collapse (Figure 8), which, whilst strictly applicable to La Palma, nevertheless serves as a model of what will happen when edifice failure occurs on Tenerife. Ward & Day (2001) revised model indicates that the tsunami, would in addition to radiating westward, be also refracted behind La Palma and within 30 minutes have reached the northern side of Tenerife. Within 1 hour all the Canary Islands would have been affected (Figures. 8A - 8F). Ward & Day (2001) based their calculations on a volume of ~500km^3 entering the Atlantic Ocean at velocities between 45 to 100ms^{-1} over a period of 800 seconds, ~13 minutes. Due to increased altitude resulting in higher gravitational acceleration and larger mass, edifice failure on Tenerife will generate a tsunami the dimensions of which can be expected to surpass the projected La Palma tsunami.

On the island of Tenerife there is evidence that the whole of the northern flank of the island is at a more advanced stage of failure. Two arms of the three-armed rift system on Tenerife enclose the northern flank of the island and have a combined length of ~40km about twice the length of the Cumbre Vieja. The third arm is acting as a buttress (Carracedo 1994, 1996). All historical volcanic activity on Tenerife has been associated with these two arms. The most recent activity was from the El Chinyero monogenetic vent which erupted in 1909. Eruptive activity becomes increasingly explosive towards the triple junction and is connected with the development of shallow magma chambers at about sea-level. The two strato-volcanoes of Montaña Teide and Pico Viejo are known to erupt explosively. The large areas covered by pyroclastic flows, ignimbrite sheets, pumice air-fall deposits etc. testify to the explosive nature of the previous Las Cañadas volcanoes I, II & III. Montaña Teide is considered to be the Las Cañadas volcano IV. The Las Cañadas volcanoes I, II & III grew for an average ~320ka, before catastrophic collapse. The current Las Cañadas volcano IV - Montaña Teide by comparison is only ~110ka.

Stalled faults on collapsing edifices are not considered unusual (Elsworth & Voight 1996). Where these occur on volcanic ocean islands such as the Canary Islands, failure planes may reach a high level of development before the edifice fails in a cataclysmic collapse. This is because islands like the Canary islands are semi-arid with most precipitation falling in the winter period. The failure planes may be lubricated by water percolating through the edifice, but still require a physical force, seismic or expanding steam (Day *et al.* 1999), to provide the impetus whereby the inertia is overcome and catastrophic failure may occur.

Eruptions at rift systems e.g. the Mid-Atlantic Ridge (MAR), normally result in each side of the rift moving away from the rift centre. The major difference between Tenerife's rifts and that of the MAR is that on Tenerife the total motion is taken up by displacing the northern flank (Figure 9). As a result, the two active arms act in the manner of a bow, with maximum displacement adjacent to the triple junction and minimal movement at the ends adjacent to the Anaga and Teno Massifs (Figure 9). Thus whilst overall the expansion may be no greater than, e.g. 2$cmyr^{-1}$, the rigidity of the southern sides of the rifts means that all the expansion is in a northerly direction and that the whole of the northern flank is moving northwards at 2$cmyr^{-1}$. Increased northward motion of the Icod Valle due to the unequal expansion of the rifts would increase loading to a level where failure could occur rapidly. This displacement is only one cause of the volcanic edifice on Tenerife being unstable.

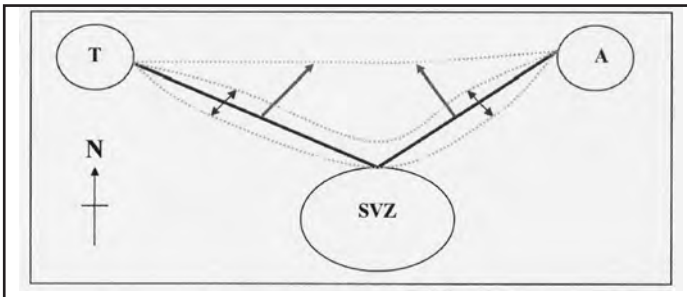

Figure. 9. Sketch of the relationship between the normal motion of active rifts – double-headed arrows, motion is equal on both sides of the rift. On Tenerife the total motion is taken up on the northern side of the rifts – single-headed arrows. The result is that the northern flank is moving at twice the rate than if the motion was being taken up on both sides of the rift. Abbreviations:- A – Anaga, T – Teno, SVZ – Southern Volcanic Zone. (GAV 16.09.2003)

There is strong field evidence which demonstrates that Montaña Teide is collapsing with the southern flank of the cone "closing" to the north, with its hinge point being the junction of the south-

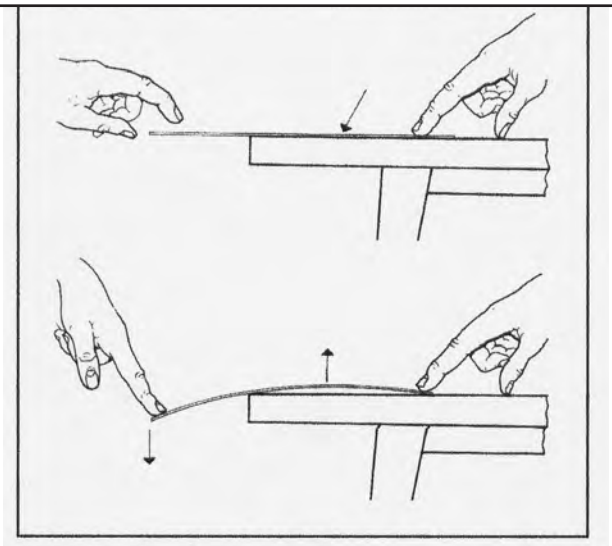

Figure. 10. The principle of rigid material flexing under load is demonstrated in this sketch. The ruler lifts upwards before it bends down. This upward flexing is common to oceanic lithosphere in subduction zones before it descend into the subduction trench. Similar processes are operating within the volcanic edifice of Montaña Teide. (Open University, 1998b.)

ern flank and the base. Martí & Gudmundsson (2000) have indicated the presence of a bulge on the southern flank of Montaña Teide, which they interpret as being related to the location of a re-entrant on the northern flank between Pico Viejo and Montaña Teide. Oceanic lithosphere as it approaches a subduction zone flexes upwards before descending into the subduction zone (Figure 10, Open University 1998b). It is considered that the southern bulge on Montaña Teide is due to the flexing of the southern flank which is in tension due to the northern flank undergoing compression "pulling" the southern flank in a northerly direction. On the northern flank of Montaña Teide, there is a conspicuous bulge, the "Northern Bulge", which is at a higher elevation than the southern bulge. It is considered that these two bulges are connected and are indicative of the forces acting on the edifice of Montaña Teide. Additionally, the edifice of Montaña Teide is rotating in an anti-clockwise direction forming the re-entrant on the northern flank. This is adding compressive forces to the southern bulge. The southern bulge is a zone of tension and compression. As a result of the anti-clockwise rotation, the edifice is moving at a tangent to the north-east away from the forces acting on it. It is considered that these three forces are acting in a positive feedback mode, in which the effect of one action increases the effect of the other forces.

Martí *et al.* (1997) have postulated that the edifices of Pico Viejo and Montaña Teide are located over the head wall of the Icod Valle. The Icod Valle is a landslide valley that has been partially infilled by eruptive material from Pico Viejo and Montaña Teide. The debris that resulted from the generation of the Icod landslide is exposed in road cuttings and is composed of boulders several metres in diameter with a coarse matrix up to 5mm in diameter (own field notes). The debris on the valley floor even though it is buried under eruptive products from Montaña Teide and Pico Viejo will not have the same structural strength that the same rock would have if it had not been subjected to failure. Ward & Day (2001) consider that on La Palma the failure plane associated with the Cumbre Vieja extends seawards and is located at unascertained depth. It is considered that similar features exist in connection with the Icod Valle.

Evidence to support these hypotheses is shown by photographs of the northern flank of Montaña Teide (Figure 11). These clearly show the northern bulge. Analysis of photographs indicates that Montaña Teide should be ~6% or ~206m higher than at present. By measuring the two angles and adjusting for the known height

Figure. 11. The above photograph shows the asymmetric profile of Montaña Teide. Looking south-west from the edge of the Orotava Valle. (Anon. from a post card)

showed that the southern flank should have an inclination of ~32° instead of ~29°. This is interpreted as indicating that the asymmetrical shape of the Montaña Teide edifice is due to forces not directly connected to any eruptive activity from the edifice (Figure 12).

The deformation that is in progress on Montaña Teide, is exacerbated by the two active arms of the rift. If vent location is considered to mark the alignment of the rifts, then the vent of Pico Viejo, Montaña Teide main vents and Montaña Blanca indicate that the Dorsal Rift passes through them. Even if Martí & Gudmundsson (2000) are incorrect in their hypothesis that the edifices of Pico Viejo and Montaña Teide are located over the head wall of the Icod Valle; an unstable edifice is implied.

Martí *et al.* (1997) claim that the Ucanca Caldera is a true collapse caldera. Part of the argument against this is the absence of a northern caldera wall (Ancochea *et al*. 1998). Field evidence indicates that the northern edge of the Ucanca Caldera may lie to the south of Montaña Teide - Pico Viejo. On the floor of the Ucanca Caldera is a line of monogenetic cinder cones (Figure 13).

These are partly buried by products from Pico Viejo and Montaña Teide, pre-dating several eruptions from Pico Viejo - Montaña Teide. The line of cinder cones aligns with the exposed end of the

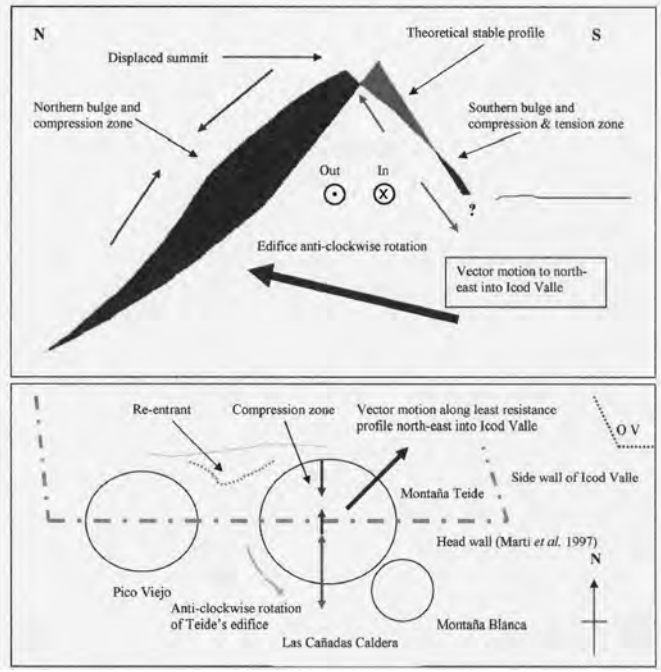

Figure. 12. Diagrammatic representation of the deformation processes that are occurring within the edifice of Montaña Teide. The edifice of Montaña Teide is undergoing tension on its southern flank – outward arrows and the edifice is being affected by rotational forces – thick arrow which is also compressing the southern bulge. The northern flank is under compression due to the southern flank being "pulled" towards it as it compresses – inward arrows It is buttressed against Pico Viejo and Montaña Blanca and presumably the buried structure within the Las Cañadas Caldera. The only "escape route" is a vectored motion towards the north-east – large thick arrow. Compare this with the profile in Figure 11. Not to scale. (GAV 18.03.2003)

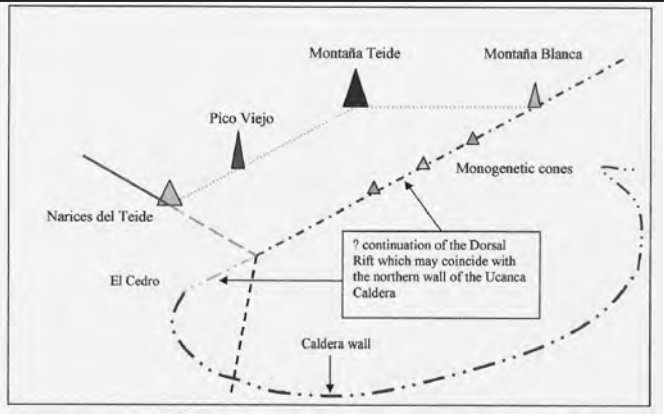
Montaña Teide
Montaña Blanca
Pico Viejo
Monogenetic cones
Narices del Teide
? continuation of the Dorsal Rift which may coincide with the northern wall of the Ucanca Caldera
El Cedro
Caldera wall

Figure. 13. The relationship of the monogenetic cones at the base of Pico Viejo - Montaña Teide to the Dorsal rift – dash – dot. The dotted line passing from the Narices del Teide – Pico Viejo – Montaña Teide – Montaña Blanca is the conventional interpretation of the relationship of the volcanoes to the rift. The dashed line is the continuation of the Santiago Rift – solid line. The dashed double dots line is an extension of the Caldera wall – dashed double dots line from El Cedro to the monogenetic cones. The small dashed line is the trend of the inactive rift. (GAV 17.06.2003)

caldera wall at El Cedro and the trend of the Dorsal Rift northwards from Montaña Blanca. It is considered that the monogenetic vents do not indicate the northern limit of the Ucanca caldera wall *senso stricto*. If the cones delineate the main trend of the rift it then indicates that the whole of the Pico Viejo - Montaña Teide - Montaña Blanca edifice is located north of the rift and is being moved northwards. This would contradict Ancochea *et al.* (1998) and support the claim by Martí *et al*. (1997) that the Ucanca caldera is a true collapse caldera.

Any of the described phenomena could cause the edifice to fail catastrophically. When combined with other phenomena the result will be a massive gravitational landslide that will be unprecedented. The massive landslide will inevitably enter the Atlantic Ocean and create a massive initial wave that may exceed that postulated as resulting from the failure of the Western flank of the Cumbre Vieja (BBC2 TV 2000).

Based on Ward & Day's (2001) data the tsunami with an initial amplitude of ~900m, will travel across the stretch of water between La Palma and Tenerife. Its potential energy will not have diminished significantly. It will devastate much of the eastern flanks of La Palma and may surge over all but the highest parts of the island. La Gomera and El Hierro will almost certainly be severely inundated and may also be temporarily submerged by the initial wave due to their lower altitudes. Ward & Day (2001) consider that the tsunami will encircle La Palma and the islands on its eastern side including Tenerife. It is reasonable therefore, to assume that a tsunami generated at Tenerife will behave in a similar manner. Large areas of Gran Canaria, Fuerteventura and Lanzarote will also be affected. On all the islands, the infrastructure will be severely or irreparably damaged. There is the potential for a huge loss of life at least in the hundreds of thousands and possibly depending upon seasonal visitor numbers, this could potentially rise to over a million people being killed in the Canary Islands alone.

Monitoring the edifice

It is important that monitoring of the edifice using several methods is carried out and the results collated. Optical observations have limited usefulness due to the length of sight lines involved. Optical observations will be curtailed in the event of fog forming and obscuring targets. If the air around the edifice is heated it will cause parallax to any optical observations which will also render the data useless. Electronic Distance Measuring devices use a laser beam and the instrument records the length of time it takes for the beam to be transmitted and returned. To do so with accuracy the air needs to be cool and dry. Heated air distorts the beam and moisture causes it to spread due to refraction and reflection by the water particles which will cause unusable data to be gathered.

Differential Geographic Positioning Systems (DGPS) offer the best method of monitoring the edifice for deformation and motion. In its basic form it needs two radio receivers, a base and a remote and a computer. DGPS can be used in any weather by one person recording the data at each survey point. DGPS requires the two receivers to record the same timing signal (common epochs) data transmitted from at least four orbiting GPS satellites. The base station is static and placed over a known point. At initialisation the two receivers need to be at least 1m apart and can be, depending upon propagation factors, up to 40km away. Visual contact with the base station is not required. The remote receiver is used to "occupy" the stations that are being monitored, usual timings of ~75 seconds. Once sufficient data has been collected the system is closed down. The two sets of data are transferred to a computer and specialist software analyses the data. The software searches for a common time signal for each observation including the initialisation. It then computes the difference in both vector and X, Y and Z co-ordinates for each occupied point. The system can cope with observations from several receivers providing they all occupy a part of the time window recorded by the base station. A group of operators could therefore cover overlapping sectors enabling a more rapid analysis to be undertaken. Accuracy of milli-metric scale ±10mm is possible using DGPS. Normal solitary user GPS receivers will not be able to provide the accuracy that monitoring the edifice of Montaña Teide – Pico Viejo will require.

Other methods of monitoring the edifice include tilt-meters, seismic, electro-resistivity, gravity etc. These methods are used to determine what is happening within the edifice and at present they are useful in enabling the "background" activity to be monitored. As a result future seismic and volcanic activity should be discovered early enough for an action plan to be activated and hopefully ensure the safety of the population.

Due to the similar composition of rocks within the Las Cañadas Caldera with those from Montaña Teide – Pico Viejo, it is unlikely that any meaningful results could be obtained by seismic profiles. Seismic surveying relies upon the differences in density that different rocks have. A seismic survey across the edifice could provide sufficient impetus to trigger a collapse and should only be undertaken after very careful consideration. It is possible that electro-resistivity may have limited use as the requirement is to be able to measure the return current. To do so successfully the current needs to be conducted through the ground. This type of survey is only likely to produce meaningful results in the late winter – early spring when melting snow is percolating into the ground.

By comparing successive amounts of data gathered over a period ranging from hours to years, it is possible to observe apparent motion relative to fixed points. To be meaningful stations would be required over the whole of the Montaña Teide – Pico Viejo edifice. They should also be located within the Las Cañadas Caldera and the Icod Valle and would need to be related to known fixed points beyond the area such as the Anaga, Teno and Roque del Conde massifs.

Mitigation of the hazard

Before steps can be taken to mitigate the hazard presented by the edifice of Montaña Teide, the hazard has to be quantified. Ward and Day (2001) have calculated that the collapse of the Cumbre Vieja in the worst case scenario will cause an initial wave with an amplitude of ~900m (Figure 8). A massive loss of property, arable land and resultant loss of income for people who live and work on the northern flank of Tenerife will occur. Many areas would be uninhabitable for several hundreds of years. Assuming that the whole of the northern flank was to fail *en masse*, it will necessitate the evacuation of several tens of thousands of people, possibly by force. Total evacuation of the island may be necessary. Because the tsunami will surge higher than its wave height safe areas will have to be prepared for occupation by displaced persons as high up the southern and western flanks as is possible, at least 1000m ASL. This will invariably cause overloading of much of the infrastructure on the southern and south-western flanks.

Conclusion

As a result of the three identified forces acting upon the edifice of Montaña Teide the whole edifice is unstable and will eventually collapse. The worst case scenario is that the whole northern flank from Teno to Anaga will catastrophically collapse en masse. This scenario is considered to be unlikely, as previous collapses on Tenerife have only involved sectors of the island – Icod, Guimar and La Orotava Valle.

A more plausible scenario will involve the strato-volcanoes of Montaña Teide and Pico Viejo. Such a collapse will almost certainly be triggered by influxes of magma and earthquakes caused by magma rising into the edifice. Properly collected and collated data together with careful analysis of the data will assist the authorities in deciding when to order a large-scale evacuation of the threatened area. The presence of tourists throughout the year increases the problems faced by the authorities and a ban on tourists might be required with forced repatriation of many who are on the islands when the danger level is triggered.

Evacuation of the threatened area will cause massive congestion on the inadequate two-lane road system which has many bad bends and steep gradients. There are plans to extend the Autopista Norte and Autopista Sur from where they finish near Puerto de la Cruz and Playa de Las Americas respectively, to form a ring road. It will enable faster evacuation of the area. The local economy on all the islands will suffer as valuable productive farm land is destroyed. Financial assistance would be required for several tens if not hundreds of years. Tourists who normally provide a valuable source of income for the many villages and towns in the area, would in all probability stay away for a considerable length of time.

This project demonstrates that on Tenerife there is cause for concern. To discover the stage of edifice failure, further research needs to be carried out. Analogue and digital models need to be developed and combined with data from various sources. Then the hazard will be properly quantified and the necessary steps taken to mitigate it.

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Personal communication from A. C. Nisbet: Subj: Spirit Lake; Date: 14/09/2003 18:14:23 GMT Standard Time; From :acnisbet@fs.fed.us; To: GerardAVallely@aol.com; Sent from the Internet:

Hi Gerard, The former altitude of Spirit Lake was 3198 feet. The current altitude of Spirit Lake is 3408 feet. This is according to the old and new U.S. Forest Service maps. I hope this has helped.Take care; Alan Nisbet, Mount St. Helens National Volcanic Monument

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Book review

The Volcano Adventure Guide by Rosaly Lopes, 2005, Cambridge University Press, 352pp, £30.00 hardback, ISBN 0521554535

This excellent book is divided into two Parts: In Part I the reader is first taken on a world tour of volcanoes starting in New Zealand and continuing around the Ring of Fire; a short detour to the Caribbean is followed by a journey along the mid-Atlantic Ridge from Bouvet Island through Tristan da Cunha and on up to Iceland; we are then transported to Africa for a journey along the Rift Valley; finally we visit the volcanoes of the Mediterranean. The second chapter covers the basic facts about volcanoes, what they are, their tectonic setting, how they erupt and the different types of magma. The explanations are clear and concise with accompanying map of the Earth's tectonic plates and sketch showing mid-ocean ridges and subduction zones. Chapter 3 describes the different types of volcanic eruptions and in Chapter 4 the subject is Visiting Volcanoes Safely and explains how dangerous they can be and gives information on how to find out about current activity before visiting any volcanic area. The final chapter in Part I gives practical advice on how to prepare for a volcanic adventure.

In the Introduction to Part II there is a classification of volcanoes by type and frequency of eruption. Detailed descriptions of the 20 chosen volcanoes are given in the next seven chapters, each covering a region or country: Hawaii, continental USA, Italy, Greece, Iceland, Costa Rica and the West Indies. The tectonic setting of each region is explained simply and clearly and there is practical information for the visitor about where to stay, availability of maps and places to visit. The field guide to each volcano includes its history of eruptions, accessibility, details of trails and hikes and how strenuous they are and fascinating information about local myths and legends associated with the volcano; eg in the guide to Kilauea the author relates the mythology surrounding Pelé, the volcano goddess, and in the chapter about Santorini there is the legend of Atlantis and the theory that the eruption caused the fall of the Minoan civilisation. At the end of each guide there are brief details of other local attractions, including nearby volcanoes or geothermal areas.

Appendices give useful sources of information on volcanic activity, including websites, and details of companies offering volcano tours. There is an extensive Bibliography and Glossary of geological terms. One of the criticisms I would make is that the word 'tsunami' which appears several times in the text does not appear in the glossary and I was also surprised that the term 'tidal wave' is used in one place to describe a tsunami. The only other small criticism I have is that the proof reading could have been better.

The book is beautifully illustrated with spectacular photographs and there are clear maps and diagrams. At £30.00 it is extremely good value and a "must have" for anyone who is fascinated by volcanoes. Even if you do not have the opportunity to visit any of the places described this book is a joy to read – but I can guarantee that you will be inspired to set off on your own volcano adventure.

Elizabeth Maddocks, BA (Open)

Murchison's Wanderings in Russia by Michael Collie and John Diemer, 2004, British Geological Survey, 474pp, £40.00 (hardback) ISBN 0852724675

Roderick Murchison was born in Scotland in 1792 and from the age of 15 spent 8 years as a soldier. Following marriage and some years as a country gentleman he took up geology as a hobby and it became his "favorite fieldsport", which he pursued enthusiastically for the rest of his life. During his latter years he became Director General of the Geological Survey, dying in harness in 1871.

In 1840 and 1841, during the middle part of his career, he undertook two major expeditions in Russia. As a consummate networking expert, he was probably the only geologist of his time who could have brought such a task to fruition. Although Murchison published his scientific findings in 1845, his private journals, in which he recorded his personal reflections on his travels, remained unpublished. "Murchison's Wanderings in Russia" is an edition of this narrative description of his expeditions edited by Michael Collie of Toronto and John Diemar of Charlotte, North Carolina. The two editors have previously edited a volume on Murchison's travels and work in Moray and have a sympathetic rapport with this period of early-Victorian Britain.

The book is fascinating both for what it tells us about travelling in Russia in the mid-19th century and for its insights into the mind and attitudes of Murchison himself. In his world working people were just that and could never become gentlemen. Women were of lower status than men and the book is full of overtly sexist observations. Unfortunately what his Russian hosts thought of this British gentleman, with his dress uniform, cast-iron folding bed and ample supply of Madeira wine remains unclear.

The text has been divided into sections corresponding to the various parts of his journeys and each section has a brief introduction by the editors. Route maps and extensive footnotes help the reader to navigate the text and clarify references which would have been clear in 1845 but are rather obscure some 160 years later. The book is published with reproductions of Murchison's map and sections from his "Geology of Russia", contained in a box bound into the book.

This is a very enjoyable read, well-produced and good value at £40. The Geological Survey is to be congratulated on its initiative in publishing such a volume to complement its existing scientific output. Perhaps it can be encouraged to publish further material from its archives related to the history of geology.

John Mather, Family member of OUGS

Vertebrate Palaeontology (third edition) by Michael J Benton, 2005, Blackwell Publishing, xi + 455pp, £29.95 (paperback), ISBN 0632056371.

This is a popular and extensively used textbook. It comprises 11 chapters, an Appendix of vertebrate classification (15pp), a 4-page glossary, 31 pages of references, and an extensive index (15pp; some entries to tertiary level). Complementing the text are 63 special boxed topics classified into three groups: 'Tree of Life Controversy', 'Exceptional Fossil(s) or Faunas', and 'Biomechanics and Behaviours'. Each chapter ends with a short section on further reading, including web sites.

The text is further complemented by 229 illustrations and diagrams plus separate, unnumbered illustrations in the boxes. A composite reconstruction drawing by John Sibbick decorates each chapter opening.

The chapters form two groups: the study of palaeontology and the evolution of the major groups of vertebrates. Each begins with a box listing key questions relevant to the group and its study. Chapters 1 and 2 set the background: 'Vertebrate Origins' and 'How to Study Fossil Vertebrates'. The first is a breathtakingly rapid sweep, but gets to the point. The second is a practical summary ranging from excavation, through analysis, research and conservation, to presentation (including TV).

The following nine chapters are devoted each to a major vertebrate group and its evolution. They are arranged according to vertebrate evolutionary chronology: 'Early Palaeozoic Fishes', 'Early Tetrapods and Amphibians', 'Evolution of Early Amniotes' [early egg-laying tetrapods], 'Tetrapods of the Triassic', 'Evolution of Fishes after the Devonian', 'Age of Dinosaurs', 'Birds', 'Mammals', 'Human Evolution'. The approach is cladistic throughout. Each chapter is a combination of subsections on straightforward vertebrate groups within the main group and a discussion of evolutionary topics relevant to the group. Examples include: molecular evidence for radiation and diversification, 'warm-bloodedness', the origin of dinosaurs, KT extinction, the origin of flight, Ice Age extinction of large mammals, and the single origin versus the multiregional model of human evolution.

The text is up to date, including recent Mesozoic birds from China and the latest human ancestors from Kenya, Chad and Ethiopia. It is dense, but clear, in spite of a huge subject matter and many still-debated topics. Benton does not avoid technical terminology or concepts - key terms are emboldened in the text. Neither does he shy away from giving his opinions or conclusions, having presented the evidence and summarised the arguments.

Although this book is designed and laid out as a textbook, a purpose that it serves well, it is an extremely useful source to consult and refresh one's memory and/or update one's knowledge and understanding of a dynamic field of research.

David M Jones BA Hons, MA, PhD, BSc Hons (Open)

Introduction to Ore Forming Processes by Laurence Robb, 2005, Blackwell Science Ltd, 373 pp, £32.50 (paperback) ISBN 0632063785

This is a textbook with many clear black and white diagrams, but no colour. The author says it's main purpose is "to provide a better understanding of the processes as well as the nature, origin of mineral occurrences and how they fit into the Earth system". The book is aimed at third and fourth level students and assumes the reader has a basic knowledge of earth science, chemistry and physics. The author also hopes it will appeal to practicing geologists as the book describes case studies of classic ore deposits.

There is an introduction and six chapters covering igneous ore forming processes; magmatic - hydrothermal ore forming processes; hydrothermal; superficial and supergene ore forming processes; sedimentary; and ore deposits in a global tectonic context. The first five chapters all begin with a list of topics and case studies, and end with a summary and a further reading list.

The case studies would look more 'interesting' if the background was in colour rather than grey. Each area is described, the minerals, their formation, mining information along with detailed diagrams and photos, but I feel they would be too basic for a mining engineer. These case studies are easy to read and informative.

The main part of the text does seem to cover all aspects of the topic, but some sections are easier to read than others. There are some very technical sections. The author makes use of abbreviations in the text so the reader either needs background knowledge or to have read the section where the abbreviation is explained. Finding the explanation can be difficult, for example PGE is referred to in a section but trying to discover what PGE stands for is hard, as the index refers the reader back to the pages where there is no explanation. The explanation was in the case study about the Merensky Reef.

The final chapter describes patterns in distribution related to geological time. Different types of deposits have occurred at different times suggesting a pattern but this could be influenced by the amount of crust preserved. This is really a trip through time, using patterns to create an overall picture. It's a very condensed history of the world!

Would I recommend this book? As a textbook yes, but as the author says, it is not for beginners. I would like to find it in a library, but would only buy it if I was studying mineralisation. It is reasonably priced. A little bit of colour would be nice aesthetically. It is not a book to sit and read from cover to cover but a useful reference book.

Wendy Hamilton BA Open Hons, B.Sc Hons